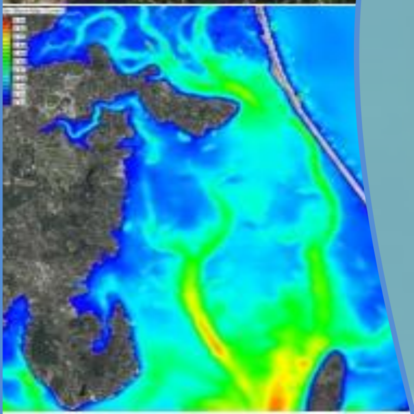

Coastal Processes Study and Resiliency Recommendations for Duxbury Beach and Bay

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December 2017

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COASTAL PROCESSES STUDY AND RESILIENCY RECOMMENDATIONS FOR DUXBURY BEACH AND BAY

December 2017

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CHAPTER 1

INTRODUCTION

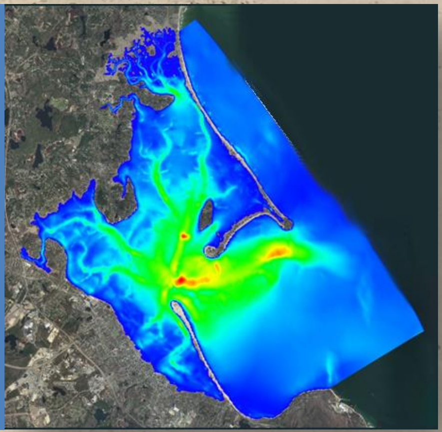
Duxbury Beach is located in the Town of Duxbury, Plymouth County, Massachusetts. The beach lies approximately 25 miles southeast of the main entrance to Boston Harbor and approximately 20 miles northwest of the Cape Cod Canal. The beach is a narrow, six-mile long barrier beach that has origins dating back over 4,000 years ago. Duxbury Beach is a dynamic environment with an ever-changing landscape. The barrier beach system is shaped by the wind, waves, currents, and tides that constantly impact the shoreline. While the Duxbury barrier beach has long served as a valuable recreational resource and critical ecological habitat, it also provides crucial storm protection to the mainland and the vibrant resources within Duxbury Bay. The beach provides protection to waterfront areas in Duxbury, Kingston, and Plymouth from coastal storms. Now, the potential acceleration of climate change, sea level rise, and increasing erosion inducing events are adding expanded pressure to the durability of the beach system. With these mounting pressures, increased resiliency of the barrier beach is paramount.

While a significant amount of historical documentation, geomorphologic studies, management and conservation plans, and ecological and beach monitoring have been conducted at Duxbury Beach; limited existing work has focused on understanding coastal processes that are influencing the current day shaping of the shoreline. As such, developing a comprehensive understanding of present day coastal processes was a critical element for building overall coastal resiliency. This report documents a study conducted to determine the coastal processes that shape Duxbury Beach and result in the ongoing evolution of the barrier beach system. Then, using those scientific findings and results, nature based adaptation measures were developed to improve the overall resiliency of Duxbury Beach. These conceptual designs are evaluated and tested using a suite of Duxbury Beach specific numerical models developed in the coastal processes assessment.

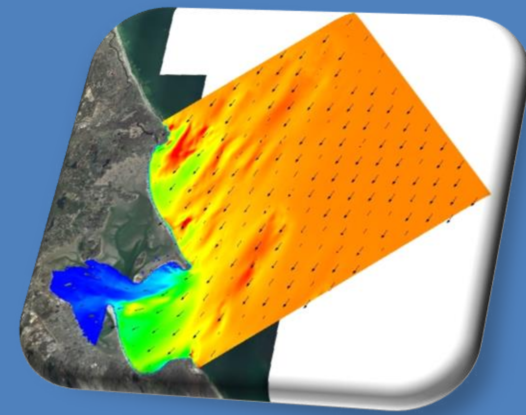
Chapter 2 presents a historical shoreline change analysis of the Duxbury Beach littoral system, extending both on the ocean and bay side of the barrier beach. The analysis used various data sets spanning from 1853 to 2015 to assess the historical nature of shoreline changes. Utilizing the historical maps, data, and information, the shoreline change analysis was used to estimate magnitude and direction of sediment transport, determine areas of erosion and accretion, temporal variations, examine geomorphic variations in the coastal zone, monitor the historic impact of anthropogenic modifications to the region, and provide verification for the sediment transport models. Shoreline change results were evaluated for a historic and contemporary time frame. Detailed assessments were conducted along the Atlantic Ocean shoreline, the Duxbury Bay shoreline, and the Saquish Beach shoreline.

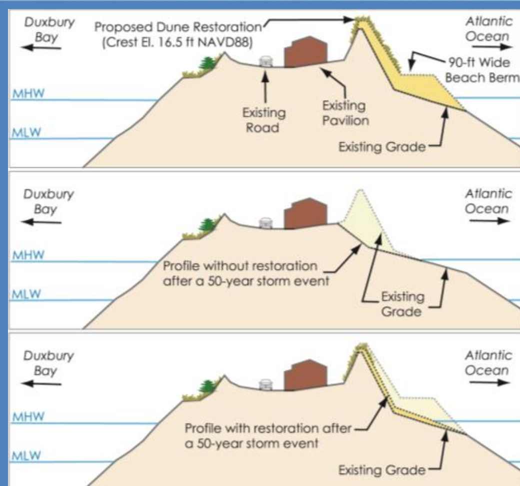
Chapter 3.presents the field data measurement program conducted at Duxbury Beach. This included measurements of tides, salinity, waves, and currents, as well as the collection of beach grain size data. The time series observations of tides (collected as pressure and then used to calculate water levels) were obtained from 4 locations around the Duxbury Beach and Bay region over approximately 30 days. These water surface elevation data were key in development of a hydrodynamic model for Duxbury Bay. Wave measurements were observed offshore of Duxbury Beach for a 2 month period and used to inform and calibrate the wave transformation modeling. Current measurements were taken within Duxbury Bay in the navigational channel paralleling the back side of Duxbury Beach. Currents were measured over a 48 day period and revealed stark contrasts in the conditions occurring during neap and spring tides. Finally, sediment samples were taken along the ocean and bayside of the barrier beach and analyzed for grain size for use in the sediment transport models.

Chapter 4 presents the development of the hydrodynamic, salinity, and temperature model of Duxbury Bay. The hydrodynamic model was used to assess the water levels, tidal currents, and storm induced currents within the bay and throughout the channels. The hydrodynamic model was applied to simulate normal tidal conditions, storm surge events, and sea level rise scenarios. While the focus of the hydrodynamic model was to assess tidal currents, focusing on potential erosive influences on the backside of Duxbury Beach, the hydrodynamic model can also be used for numerous other purposes. For example, the model can be used to evaluate water quality or sediment transport patterns within the bay, tidal flushing, potential marsh restoration projects, potential dredging projects, impacts of various modifications to Duxbury Bay, and countless additional studies that would require the hydrodynamics of the Bay as baseline information. As such, this model is readily available for the Duxbury Beach Reservation or Town of Duxbury to apply in other projects.



Chapter 5 presents the results of the regional wave modeling effort. Wave transformation modeling was conducted on a regional scale to propagate offshore waves towards Duxbury Beach. Chapter 5 and Appendix 5-A provide details on the development, verification, and results of the transformation-scale modeling effort. To quantify the wave impact along Duxbury Beach, site-specific wave conditions were determined using wind data, wave data, and the developed numerical wave transformation model for Duxbury Beach. Average annual wave conditions, as well as conditions occurring during high energy storm events were evaluated. The information generated by the wave transformation modeling was utilized to produce forcing information for how sediment is transported along and across Duxbury Beach.





Chapter 6 presents the results of the sediment transport modeling, including the sediment movement that occurs in both the alongshore and cross-shore directions. Both annual average conditions and storm events are evaluated to determine sediment transport rates along the shoreline and erosion conditions at site specific locations. The sediment transport models are physics-based models that are able to predict sediment transport trends in the presence of time-variable waves. The sediment transport modeling is also used to assess the performance of potential resiliency options and designs. For example, the service life of a regional beach nourishment project is evaluated and the performance of dune restoration projects against storm events can be determined.

Chapter 7 presents conceptual resiliency adaptation for Duxbury Beach founded in the science and physical processes acting on the barrier beach system. Due to the delicate balance of the ecosystem and natural landscape, resiliency options and engineering concepts are green in nature and designed to preserve the ecological and recreational usages, while balancing the need for improved storm damage protection. A larger-scale regional approach, as well as site-specific resiliency adaptations, are evaluated for critical locations along the beach. These local resiliency measures are intended to be more near-term attainable and fiscally manageable solutions. For each conceptual adaptation, a priority level, developed with the Duxbury Beach Reservation Technical Committee, and an expected time frame is presented.

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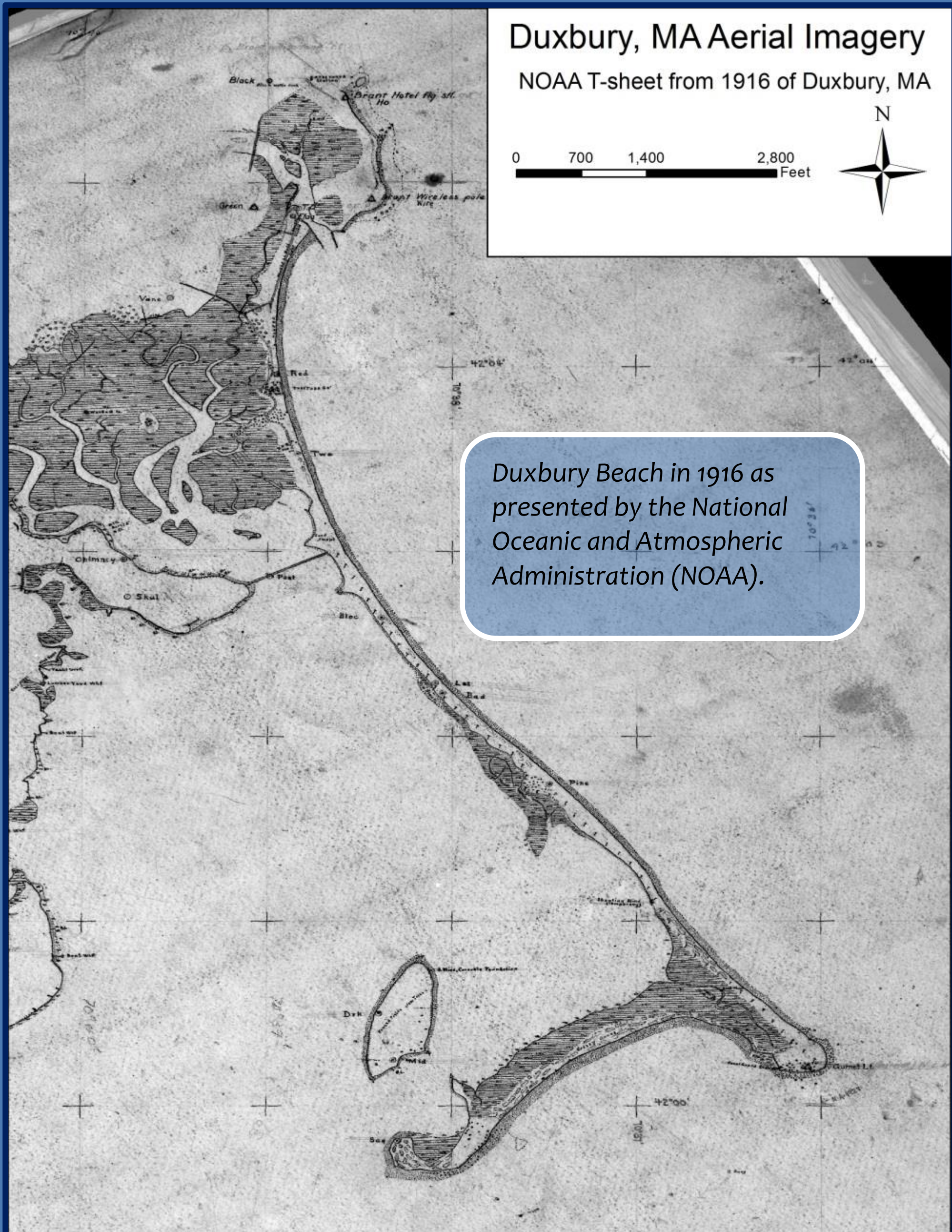
CHAPTER 2

HISTORICAL SHORELINE CHANGE

DATA COMPILATION AND ANALYSIS



Duxbury Beach in 1916 as presented by the National Oceanic and Atmospheric Administration (NOAA).

Waves, winds, currents, tides, and rising seas all work together to shape the coastline of Duxbury Beach. Overtime, significant changes to the barrier beach have occurred. For example, since the mid 1800s, the beach has moved landward by approximately 300 feet and has narrowed by approximately 250 feet in the vicinity of the Powder Point Bridge. More recently, human activity has also contributed to the evolution of the beach through the construction of shore protection structures (both locally and regionally), as well as through adding sediment to the system. For example, the construction of seawalls along the Scituate and Marshfield shorelines has reduced the natural sediment supply to Duxbury Beach. Therefore, both natural processes and anthropogenic changes have resulted in ongoing transformations to the shoreline.

In order to quantify the spatial and temporal changes in the Duxbury Beach shoreline, a computer based mapping methodology, developed by the United States Geological Survey (USGS), was used to compile and analyze historical shoreline positions along Duxbury Beach. Using the most accurate data sources and compilation procedures available, both short-term and long-term changes occurring along the shoreline were calculated. This historical shoreline change analysis was conducted for the entire 15 mile coastline along Duxbury Beach on both the bay and ocean shorelines. The study area extended from the entrance of Green Harbor on the ocean side to the southern end of the barrier beach, around Saquish Head, and then back north along the bay side shoreline to the Duxbury Beach Reservation parking lot near the Pavilion.

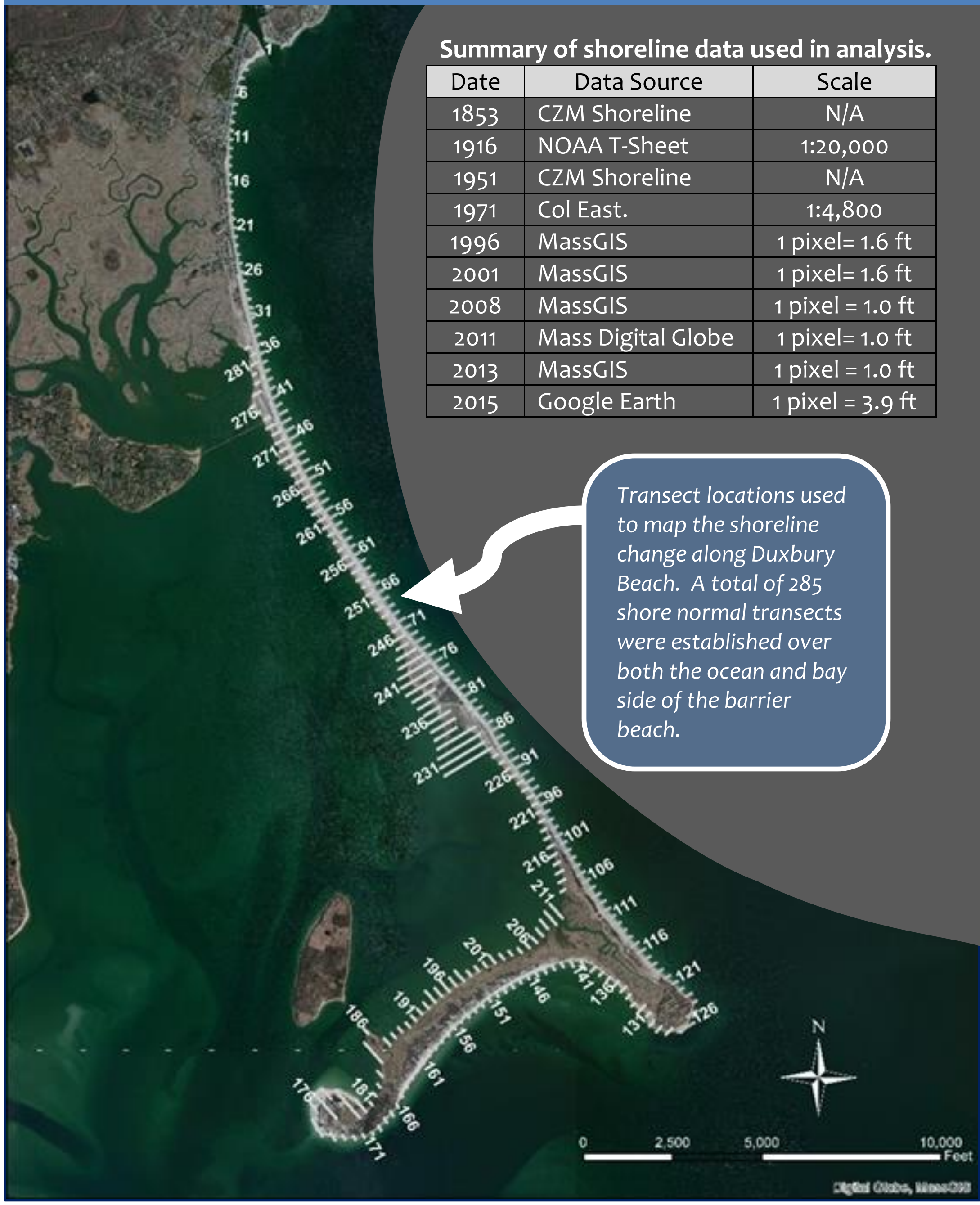
The aerial photographs and historic maps utilized for the analysis ranged from 1853 to 2015 and provided a reasonable temporal distribution of available data for the Duxbury Beach region. Aerial photography was selected based on clarity and scale in order to use the highest quality photographic data. Although additional aerial photographs from other sources and years were available for Duxbury, only aerial photography at the appropriate extent, scale and time interval were used for this analysis.

DATA COMPILATION AND ANALYSIS

In order to determine the changes occurring along the shoreline, a number of steps were taken to analyze the aerial photographs. The analysis approach included:

- **Distortion correction** – Aerial photographs can contain a variety of distortions that are corrected using computer-aided cartographic mapping software.
- **Geo-referencing** – Geo-referencing was performed by identifying a series of evenly distributed control points on the images for which real world x, y coordinates were known. The 2013 MassGIS digital orthoimagery was utilized to obtain ground control points.
- **Shoreline delineation** – Interpretation of each photograph was completed to identify a shoreline position. The horizontal position of the high-water shoreline, as recognized on the beach and on photography, was determined using a hierarchy of criteria dependent on morphologic features present on the beach. The primary criterion was the wet-dry line along the beach (approximate mean high water line).
- **Quantification of shoreline change** – Once the shoreline position data were compiled, spatial and temporal changes in the data were quantified. This includes calculations of shoreline movement and annual rates of shoreline change.
- **Error Analysis** - A certain measure of error will occur when estimating shoreline positions. As such, an error analysis is conducted to detail a total error for each dataset.

Complete details on the methodology, analysis, and associated error estimates completed as part of the Duxbury Beach historical shoreline change analysis can be found in Appendix 2-A. Results of these analyses are used not only to determine the historic changes that have occurred along Duxbury Beach, but also to validate the sediment transport assessment by comparing historic rates of change to predicted sediment transport patterns.



Summary of shoreline data used in analysis.

Date	Data Source	Scale
1853	CZM Shoreline	N/A
1916	NOAA T-Sheet	1:20,000
1951	CZM Shoreline	N/A
1971	Col East.	1:4,800
1996	MassGIS	1 pixel= 1.6 ft
2001	MassGIS	1 pixel= 1.6 ft
2008	MassGIS	1 pixel = 1.0 ft
2011	Mass Digital Globe	1 pixel= 1.0 ft
2013	MassGIS	1 pixel = 1.0 ft
2015	Google Earth	1 pixel = 3.9 ft

SHORELINE CHANGE RESULTS

In order to compute the changes in shoreline position, a series of shore-normal transects were established. A total of 285 shore normal transects were established at 250 foot evenly spaced intervals. At each transect, distances of shoreline movement were calculated, and average annual rates of shoreline change were determined using the time intervals between shorelines. Changes in shoreline position (and rates of change) were calculated for three specific time periods, which included:

- 1853 to 2015 – Time period representing long-term rates of change along Duxbury Beach
- 1853 to 1971 – Time period representing historic rates of change along Duxbury Beach prior to significant Duxbury Beach Reservation restoration measures
- 1996 to 2015 – Time period representing contemporary rates of change that includes Duxbury Beach Reservation restoration actions (e.g., dune restoration, vegetative plantings, etc.)

Additionally, while Massachusetts Coastal Zone Management (CZM) has completed shoreline change analysis for the coastlines of Massachusetts, including Duxbury Beach, the shoreline change analysis presented herein represents an enhancement of the CZM data through:

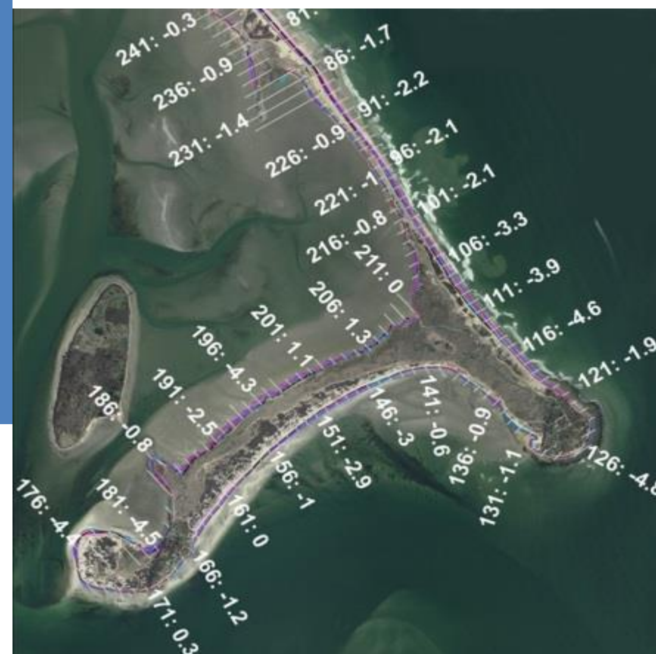
- Addition of more shorelines in time
- Addition of more recent shorelines (after 2009)
- Avoidance of the CZM 1994 shoreline, which is known to be poorly delineated and influences the shoreline change rates
- Calculation of distinct time periods for shoreline change that provide more site-specific information than provided by the CZM analysis. For example, the impacts of construction of a coastal structure can be determined by evaluating pre- and post-construction shoreline change conditions.

Full shoreline change results, including presentation of all map panels and tables of shoreline change rates can be found in Appendix 2-A.

Shoreline Change Rates (1853-1971)

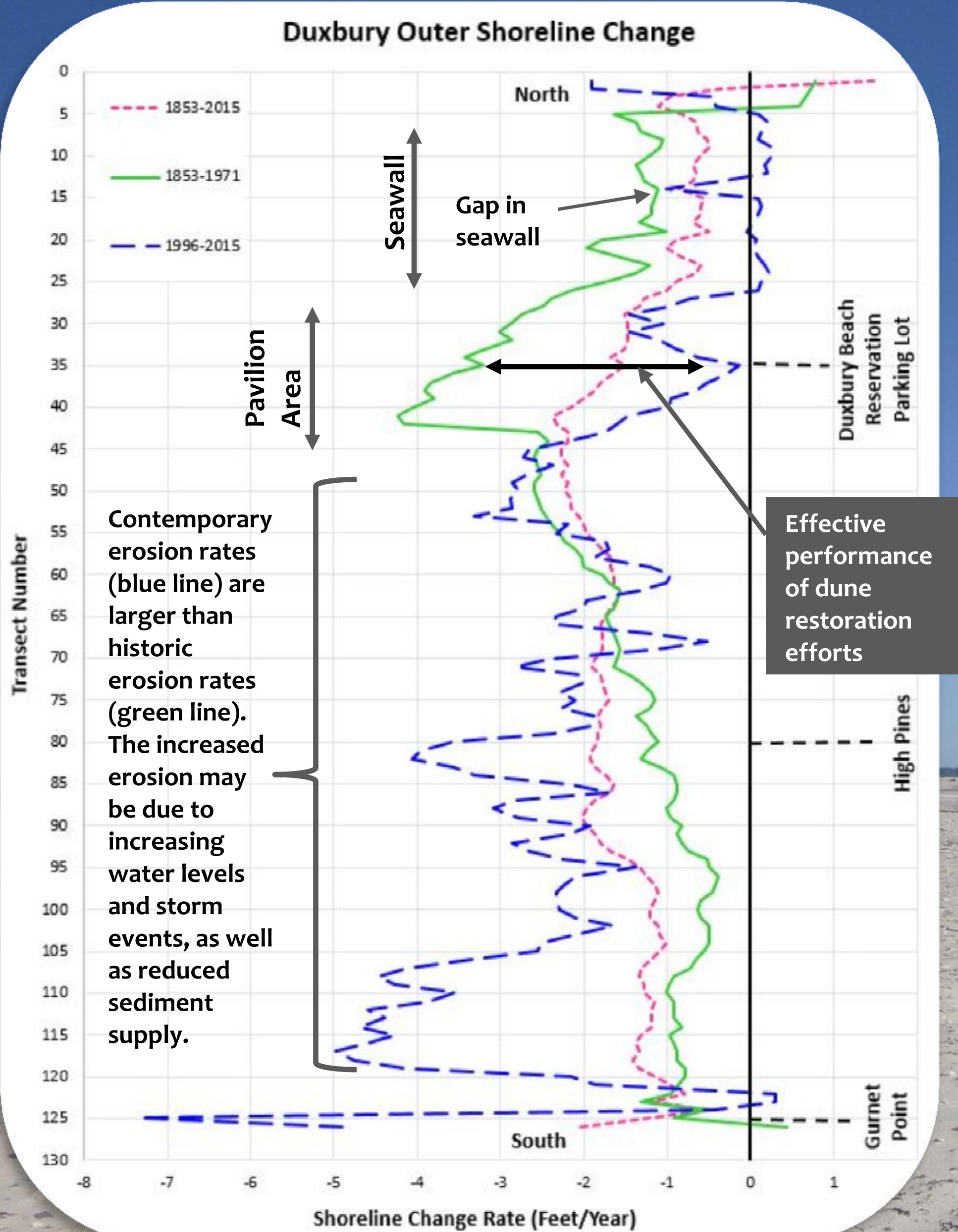
Rates are presented in ft/yr. Negative values indicate shoreline retreat, while positive values indicate shoreline advance. Background imagery from 2013.

Comparison of historic (top panel) and contemporary (bottom panel) shoreline change rates. Values on figures show Transect #: Change Rate. Rates are presented every 5th transect. The analysis indicates that along the Atlantic Ocean shoreline erosion rates have increased in the contemporary time frame. For example, at transect 111, the historic erosion rate was -0.9 ft/yr, while the contemporary erosion rate is -3.9 ft/yr. This indicates an acceleration of shoreline retreat due to increased water levels, storm events, and reduced sediment supply.



Shoreline Change Rates (1996-2015)

ATLANTIC OCEAN SHORELINE



Comparison of shoreline change rates for 1853-2015 (red broken line), 1853-1971 (green line), and 1996-2015 (blue broken line) time periods along the Atlantic Ocean side of Duxbury Beach. Rates are presented in feet per year. Transect numbers are presented on the vertical axis from Green Harbor Jetty (top) to Gurnet Point (bottom). Negative shoreline change rates indicate shoreline retreat, while positive values indicate shoreline advance.

Long-term rates of shoreline change along Duxbury Beach were calculated for the period of 1853 to 2015. The 162 year time interval covered by the data describes the long-term trends in shoreline change. Pre-1971 rates of shoreline change were calculated for the period 1853 to 1971. The 118 year time interval covered by these data describes trends in shoreline change before a majority of beach management activities were implemented at Duxbury Beach. Finally, contemporary shoreline change results are shown between 1996 and 2015. This time period represents a 20 year period where more active beach management was conducted by Duxbury Beach Reservation (DBR). By plotting shoreline rates for the three time periods, differences and changes between time periods can be assessed.

Between transects 6-26, a seawall constructed in the 1950s has limited shoreline retreat. Historic rates (1853-1971) in this area were between -1 to -2 ft/yr, however, contemporary rates (1996-2015) were reduced to near zero with the seawall in place. While the seawall limits erosion for the area directly landward, the structure also reduces the available sediment supply.

Seawall

Pavilion Area

Between transects 27-44, the area surrounding theDuxbury Beach Park pavilion, the contemporary retreat is signficnatly less than the historic retreat. Concerted dune restoration efforts completed by the DBR have been effective in reducing erosion rates from -3 to -4 ft/yr down to -1ft/yr or less. This demonstrates the effective nature of green resiliency adaptations.

SAQUISH BEACH SHORELINE

Long-term rates of shoreline change along the southern facing shoreline of Duxbury Beach, including Saquish Beach, were calculated for the period 1853 to 2015. Pre-1971 rates of shoreline change rates were calculated for the period 1853 to 1971 and contemporary shoreline change results are shown between 1996 and 2015. By plotting shoreline rates for the three time periods, differences and changes between time periods can be assessed.

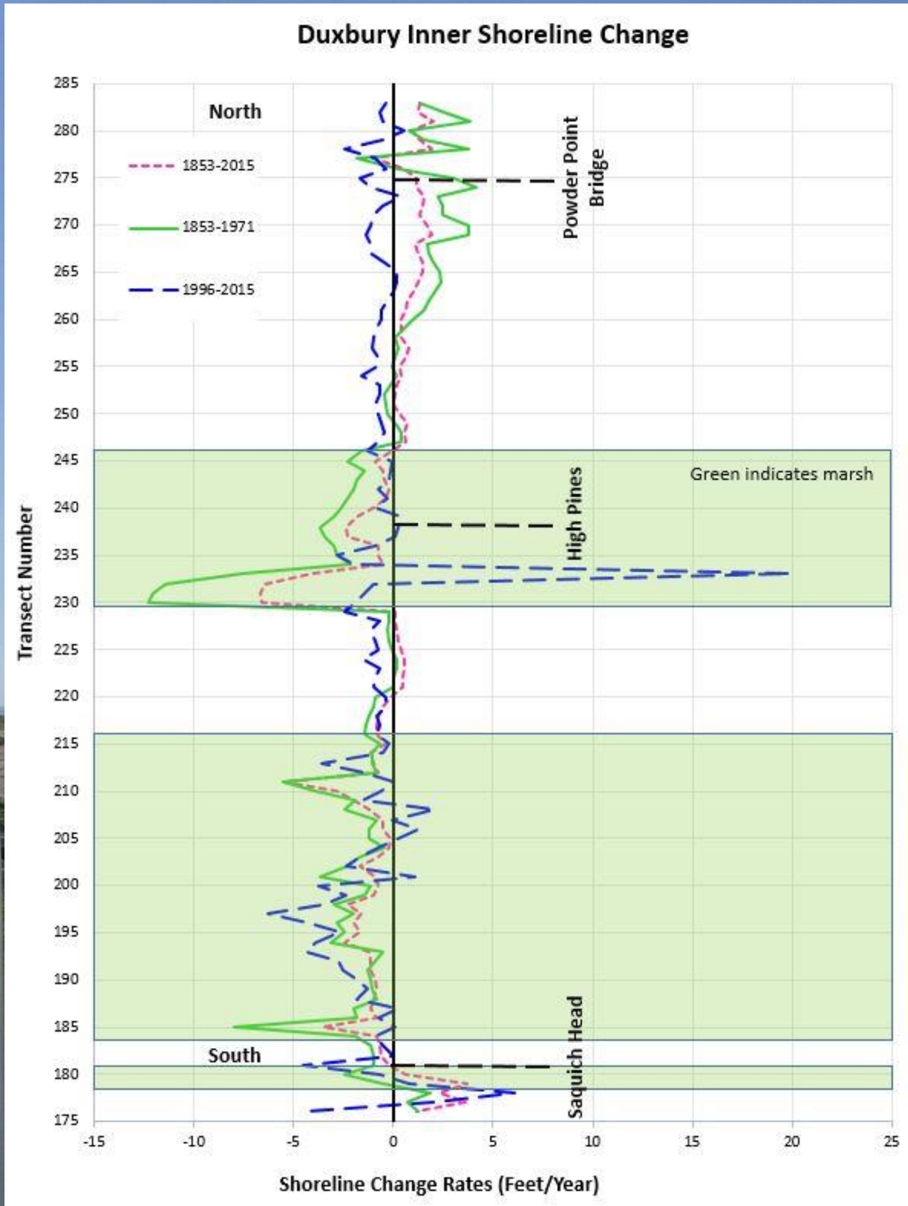
Generally, erosion and accretion rates along this shoreline are lower than the Atlantic Ocean facing shoreline, which is to be expected given the reduced wave exposure for this area. Over the long-term (red broken line), the shoreline has been relatively stable with erosion rates that are generally less than 1 ft/yr and average -0.3 ft/yr.

Historic shoreline change rates (green line) have also been relatively stable with an average erosion of rate of -0.04 ft/yr. Contemporary shoreline change rates (broken blue line) show more variability, partially due to a shorter evaluation time frame. During the contemporary time frame, shoreline retreat has increased to an average rate of -0.8 ft/yr.

The area in the vicinity of 8th street where accelerated erosion rates of up to 4 ft/yr have been occurring. Historically, this had been a relatively stable location; however, recently erosion rates have been much larger.

Comparison of shoreline change rates for 1853-2015 (red broken line), 1853-1971 (green line), and 1996-2015 (blue broken line) time periods along the Saquish Beach shoreline. Transect numbers are presented on the horizontal axis spanning from West (left) to East (right). Negative shoreline change rates indicate shoreline retreat, while positive values indicate shoreline advance.

DUXBURY BAY SHORELINE



Comparison of shoreline change rates for 1853-2015 (red broken line), 1853-1971 (green line), and 1996-2015 (blue broken line) time periods along the Duxbury Bay shoreline. Rates are presented in feet per year. Transect numbers are presented on the vertical axis from Saquish Head (bottom) to Powder Point Bridge (bottom). Negative shoreline change rates indicate shoreline retreat, while positive indicate shoreline advance. Green zones indicate areas where salt marsh is present along the shoreline, indicating less confidence in delineation.

Long-term rates of shoreline change along the Duxbury Bay shoreline were calculated for the period 1853 to 2015. Pre-1971 rates of shoreline change rates were calculated for the period 1853 to 1971 and contemporary shoreline change results are shown between 1996 and 2015. By plotting shoreline rates for the three time periods, differences and changes between time periods can be assessed.

Significant portions of the Duxbury Bay shoreline consist of fringing salt marshes that have been eroding over the long-term. Specifically, the landward side of Saquish Beach, between transects 179 and 220, comprises a large salt marsh resource that has been eroding over the long-term, historical, and contemporary time periods. This stretch of salt marsh has been eroding at an average rate of approximately 1 to 2 feet per year. The other significant salt marsh area, on the landward side of High Pines between transects 230 and 246, has been affected by even larger erosion rates. Historically, this salt marsh has eroded at rates up to 12 ft/yr. Contemporary erosion of the High Pines salt marsh complex continues (averaging approximately 1.0 ft/yr), although it is highly variable, likely due to the slumping material and changing morphology of the marsh creeks and plains.

High Pines Salt Marsh

The northern end of the Duxbury Bay shoreline (transects 250 to 283) consists of more sandy beach material. Historically, this area has been accreting, or stable, with average rates of approximately 1.0 ft/yr. However, the more contemporary time period shows erosion along this stretch of beach with rates averaging -0.7 ft/yr.

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CHAPTER 3

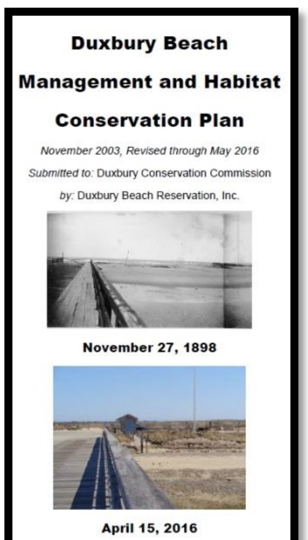
DATA COLLECTION

WOODS HOLE GROUP

EXISTING DATA AND STUDIES

Duxbury Beach is a valuable resource, not only because of the inherent ecological and recreational benefits, but also because it serves as protection to the Bay, Duxbury, Kingston, and Plymouth from storms. Without maintenance and management, Duxbury Beach will continue to evolve; advancing landward to one day perhaps weld to the mainland (Rosen and Fitzgerald, 2014) or perhaps breach, erode and slowly disappear under storm and sea-level rise pressures. A significant amount of historical documentation, geomorphologic studies, management and conservation plans, and ecological and beach monitoring have been conducted at Duxbury Beach. However, limited existing work has focused on understanding coastal processes that are influencing the current day shaping of the shoreline. As such, developing a comprehensive understanding of present day coastal processes was a critical element for building overall coastal resiliency.

In order to understand the coastal processes at Duxbury Beach, and ultimately continue to build resiliency, a data collection and numerical modeling program was undertaken. The data collection component of the study was geared towards understanding the physical processes at work, and providing valuable information for building and verifying the numerical modeling system. The data collection effort consisted of gathering existing data, as available, and new field measurements (waves, currents, and tides).


Duxbury Beach

Management and Habitat

Conservation Plan

November 2003, Revised through May 2016

Submitted to: Duxbury Conservation Commission

by: Duxbury Beach Reservation, Inc.

November 27, 1898

April 15, 2016

A number of valuable documents and studies were utilized to assist in the development of this study. These include, but are not limited to:

- *The 2016 Beach Management and Habitat Conservation Plan (DBR)*
- *The 2014 study of Morphology and Coastal Processes Along Duxbury Beach (Rosen and Fitzgerald)*
- *Numerous Endangered Species Reports and Bird Nesting Reports*
- *The Duxbury Sunken Forest (Gontz et al., 2013)*
- *The Duxbury Beach Book (Kearney and Foster, 2007)*

While site-specific wave data were collected at Duxbury Beach, as presented in this chapter, there are also offshore wave data available. Time series of wave hindcast data from the Wave Information Study (WIS) and wave measurements from the National Data Buoy Center (NDBC) were utilized to define the long-term offshore wave climate. Details on these data can be found in Chapter 5 and Appendix 5-A.

A significant amount of bathymetric information was required to simulate the sea state in the numerical models. Existing data sources were utilized extensively and included data from the National Oceanographic and Atmospheric Administration (NOAA) and the United States Army Corps of Engineers (USACE). Details on these data can be found in Chapter 4 and Appendix 4-A.

Existing topographic data were obtained from MassGIS as a Light Detection and Ranging (LiDAR) data set from 2011. Local beach survey data were also available (Rosen and Fitzgerald, 2014), but were of limited use since they were not vertically or spatially geo-referenced.

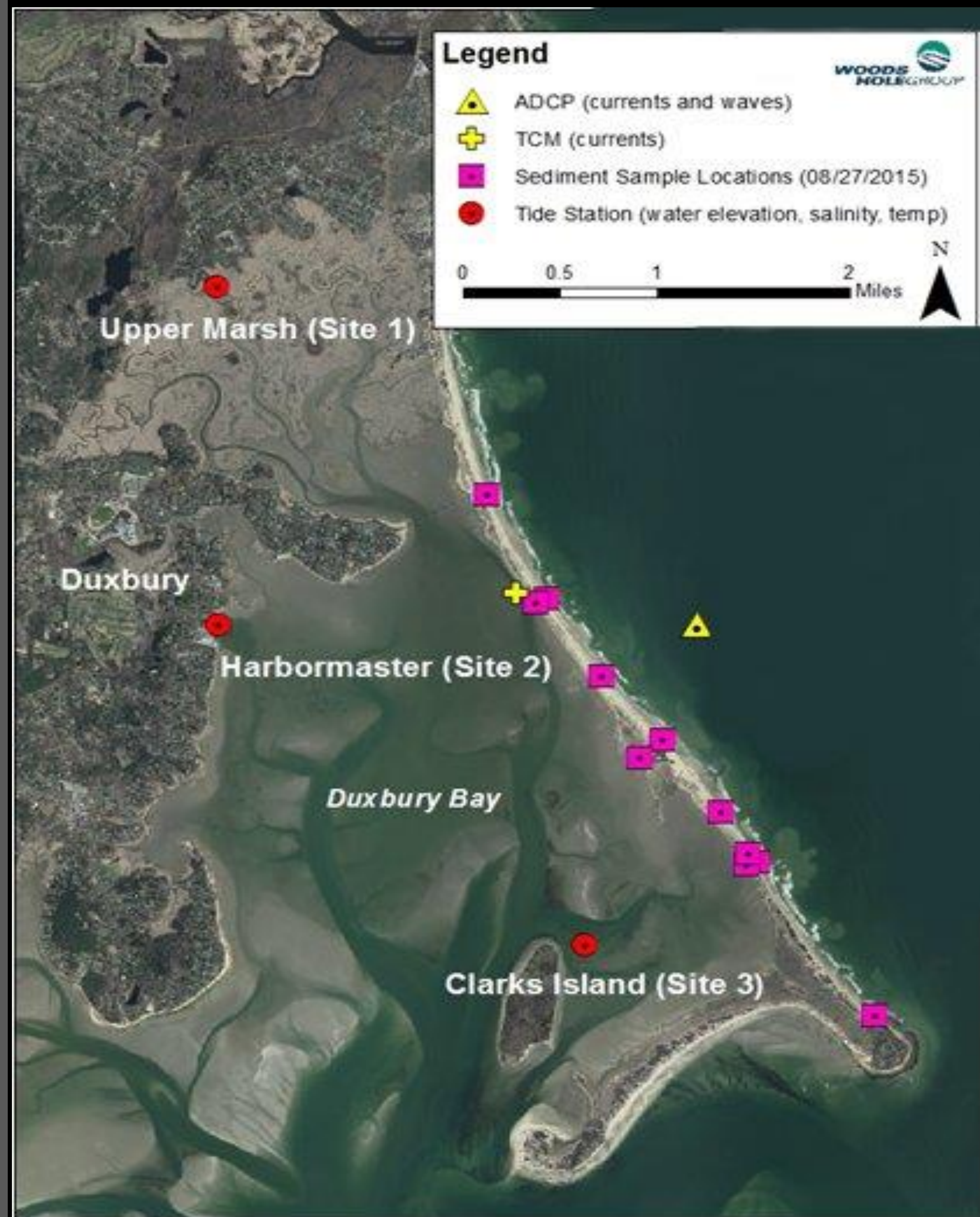
Other meteorological data were also utilized to help define the physical conditions at Duxbury Beach and within the Bay. These data included wind and precipitation data acquired from local National Weather Service stations.

NEW FIELD MEASUREMENTS

In addition to the existing data and studies available for Duxbury Beach, site-specific physical processes data were also collected for this study. These new field measurements, as shown in the adjacent figure, consisted of (1) water surface elevation, salinity, and temperature at three locations within Duxbury Bay (red circles); (2) nearshore wave and current observations just offshore of Duxbury Beach (yellow triangle); (3) tidal currents within the navigational channel along the backside of Duxbury Beach (yellow plus); and (4) sediment samples along the Duxbury Beach on both the Ocean and Bay side of the barrier beach (pink squares).

Field observations were completed during the late spring and early summer of 2015 and provided valuable information on the hydrodynamics, physical processes, and sediment characteristics throughout the region. The data alone provide insight on the processes shaping the beach, and also served to calibrate and validate the site-specific models developed for the region.

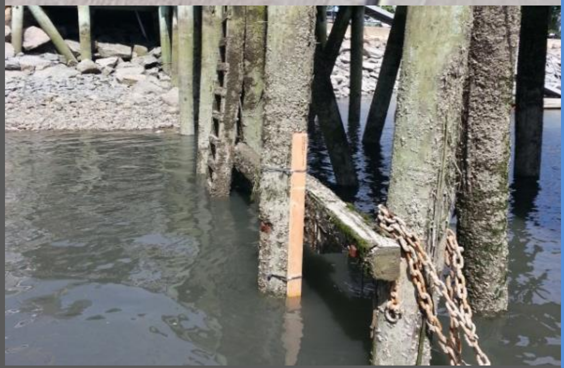
- The tide observations were used to calibrate the hydrodynamic model of the Duxbury Bay system. This included the processes of tidal exchange throughout the embayment and marsh system. Model results were calibrated to the data observations at Clarks Island, the Harbormaster dock, and the upper marsh stations. This resulted in a calibrated hydrodynamic model (Chapter 4) that was used to assess velocity and erosion potential along the backside of the barrier beach, but also is available for numerous other assessments in Duxbury Bay (i.e., dredging, marsh restoration, tidal flushing, etc.).
- The tidal current measurements were used to gain an understanding of the temporal velocity changes at the erosive locations occurring along the bayside of the shoreline, as well as validate the hydrodynamic model of the Duxbury Bay system.
- The wave observations were used to validate the wave transformation model (Chapter 5).
- The sediment samples were used as input to the littoral sediment transport modeling along the ocean side of the barrier beach.



TIDE AND SALINITY DATA

Water surface elevation, salinity, and temperature time series data were collected at three locations within the Duxbury Bay system. These data were observed over approximately 30 days from June 6 to July 7, 2015. Additionally, the offshore wave system also collected water surface elevation measurements. Tidal elevations in Duxbury Bay were measured using Woods Hole Group Seapac 2100 pressure gauges. Each tide gauge contained a Paroscientific DigiQuartz pressure sensor (0.015% accuracy and 0.0015% resolution) coupled to a data logger. Each of these instruments measured pressure continuously, recording the average pressure over 3.75 minute intervals.

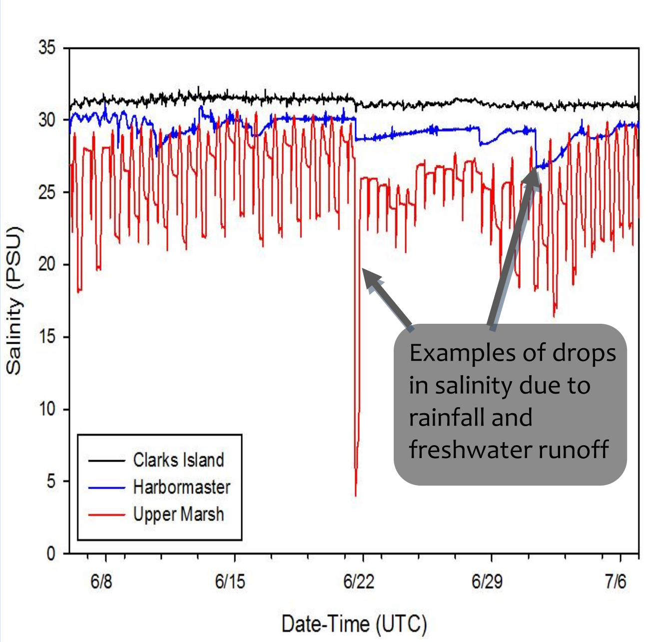
Each tide gauge measured the water and atmospheric pressure above the instrument. In order to estimate the water level (gauge pressure), the atmospheric pressure was removed from the measured signal. Subsequently, pressure data were converted to water surface elevation using the hydrostatic relationship based on the density of water. In order to reference the tide gauges to a common vertical datum, tide data from each gauge were referenced to the North American Vertical Datum (NAVD) of1988.



A Woods Hole Group Seapac 2100 tide gauge system. At the Harbormaster dock location, the Instrument was securely fixed to a 2x4 and attached to a one of the dock piles. By attaching the tide gauge to a 2x4, the instrument could be lowered deep enough to ensure the instrument would remain submerged for the entire tidal cycle. At the other locations (Clarks Island and Upper Marsh), the instruments were secured to a pipe anchor in driven into the seafloor.

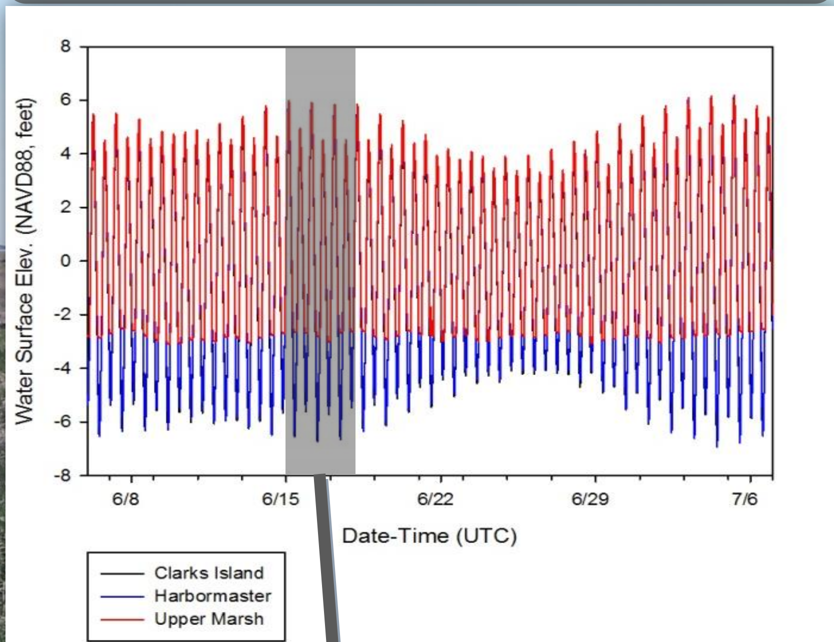
Location of tide gauge in the Upper Marsh of Duxbury Bay. All gauges were surveyed into a vertical datum (North American Vertical Datum of 1988) using an RTK-GPS system.

Salinity observations at the three tide stations. Salinity is presented in Practical Salinity Units on the vertical axis. Salinity levels at Clarks Island remain steady, matching the Atlantic Ocean, while more fluctuation in values appear in the upper parts of Duxbury Bay (Upper Marsh) due to freshwater influences. Precipitation effects can be seen both at the Harbormaster and Upper Marsh stations.

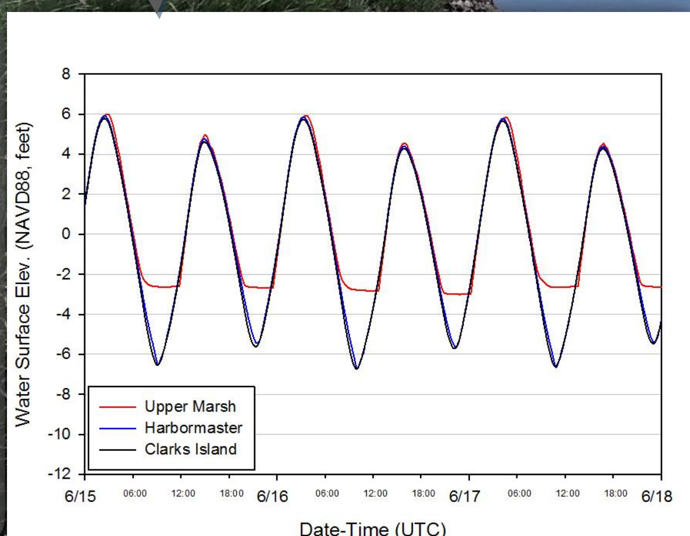


TIDE AND SALINITY DATA

Water surface elevation time series over the full deployment time period. The vertical axis shows water surface elevation in feet NAVD88, while the horizontal axis shows date.



Close-up of water surface elevation results between June 15 and June 18, 2005.

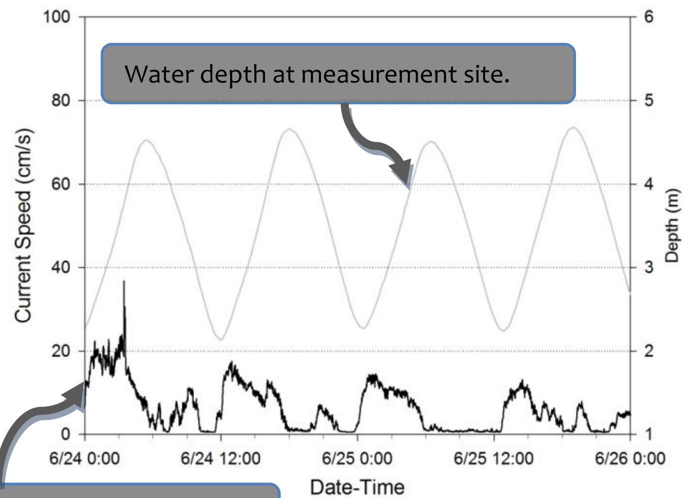


The water surface elevation (tide) data show two high tides and two low tides each day due to the influence of the moon and the sun. During a typical day, one of the high tides is higher than the other, and one of the low tides is lower. This is typical of a semidiurnal tidal cycle prevalent in the northeast. The spring and neap tides are also easily observed in the signal. During the spring tides, also known as moon tides, the tidal range in Duxbury Bay is approximately 10 to 12 ft. However, during neap tides, the tidal range is reduced to approximately 8 ft. While there is little tidal attenuation (or tidal dampening) between the Clarks Island and Harbormaster tide stations, the observations at the upstream tide gauge in the upper marsh (red line) shows a reduction in the tidal range. This reduction is primarily at low tides (i.e., the low tides in the marsh are higher). At the location where these measurements were collected, this is not due to poor drainage capacity or a restriction, rather that these marsh channels drain to shallow levels or dry out during a low tide in Duxbury Bay. These data are used extensively in the development of the hydrodynamic modeling presented in Chapter 4.

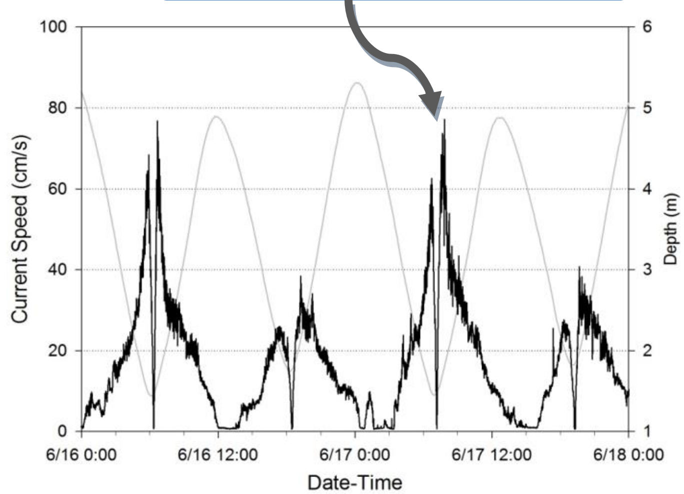
CURRENT MEASUREMENTS

The current data within the navigational channel revealed a significant difference in the current regime during neap tide versus spring tide. During spring tides currents reached peak speeds of approximately 80 cm/s, while during neap tides current speeds only had peaks of approximately 20 cm/s. There was also a significant difference in when these maximum speeds occurred in the tidal cycle.

During neap tides, the currents speeds are at a maximum during a rising (flood) tide indicating a flood dominant current and sediment movement condition (sediment moving into the bay). Generally velocities are small during neap tide conditions.



Current speed at measurement site.



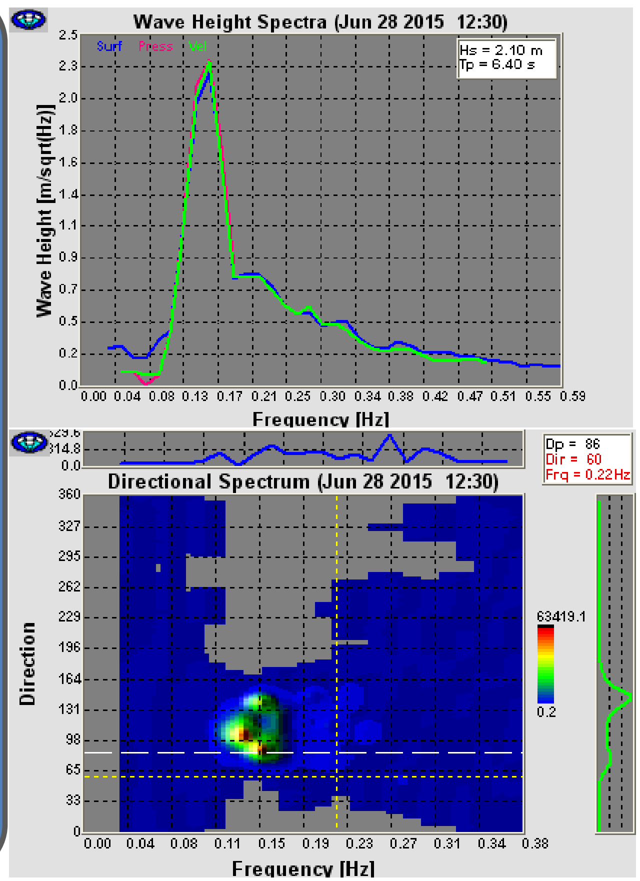
During spring tides, the currents speeds are at a maximum surrounding slack low tide and occur both during ebb and flood flows indicating a shallow water dominant condition Velocities are much larger during spring tide conditions.

In addition to the tide, salinity , and temperature data collected within Duxbury Bay, current velocities were also measured within the navigation channel that runs adjacent to the bayside of the barrier beach (see Page 3-3). This location has been experiencing significant erosion to the point mitigation measures were taken in 2006-2007 through the construction of a cobble berm. However, the ongoing threat of erosion at this site continues. The adjacent navigational channel allows significant velocities to develop along the bayside shoreline, especially during storm events. Therefore, current data were measured at this location over approximately 48 days, overlapping the entire time the tide gauges were deployed. These data were used to evaluate the fluctuations in tidal currents that occur along the bayside of the barrier beach, as well as inform the development of the hydrodynamic model for the entire bay.

A Lowell Instruments, LLC Tilt Current Meter (TCM-1) was deployed in the navigational channel and used to measure the currents. *"The TCM-1 Tilt Current Meter measures current using the drag-tilt principle. The logger is buoyant and is anchored to the bottom via a short flexible tether. Moving water tilts the logger in the direction of flow. The TCM-1 contains a 3-axis accelerometer and 3-axis magnetometer for measuring tilt and bearing. The resulting orientation data are converted to current by applying calibration coefficients."* (www.lowellinstruments.com).

The ADCP system was deployed in a trawl resistant bottom mooring along with a pop-up buoy and an acoustic pinger to aid in the recovery of the mooring. The ADCP system was deployed just offshore Duxbury Beach (as shown on Page 3-3) in approximately 38 feet of water.

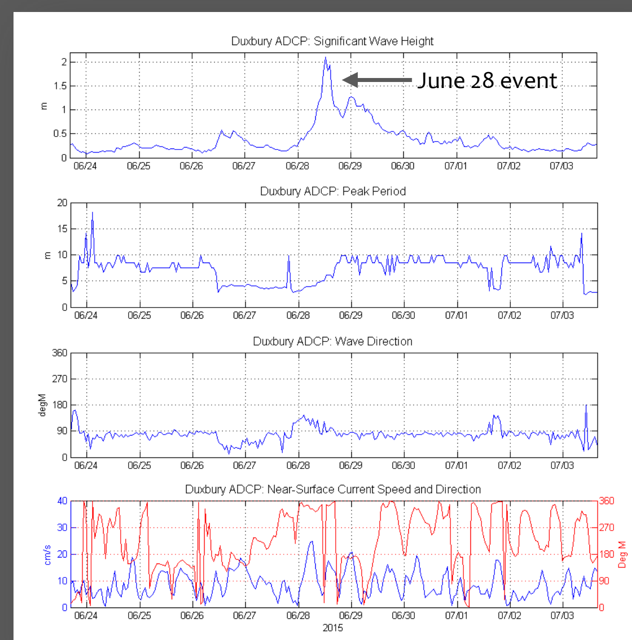
While the event on June 28, 2015 does not represent a major storm event, it did produce peak wave heights of over 7.5 feet, with significant waves of 6.9 feet. The wave height spectra (a measure of the energy as a function of wave frequency) and the directional spectrum (a measure of the energy as a function of frequency and direction) are shown here. The event had a narrow spread with most of the energy arriving from the east and east-southeast.



WAVE MEASUREMENTS

The wave data were a critical component of the overall project and were used to provide an understanding of wave propagation within the vicinity of Duxbury Beach, as well as to provide validation data for the numerical wave transformation model. A bottom-mounted Acoustic Doppler Current Profiler (ADCP) was deployed on May 14th, 2015 and measured directional waves, currents, and water depth for just over two months.

Since waves were only collected for a limited time period (in the summer), the wave measurements do not represent the overall wave climate in the vicinity of Duxbury Beach, which undergoes significant changes during the winter months versus the summer months. For example, northeasterly storm waves are not identified within the deployment time period; however, they represent a significant process identified in longer time period regional data records. Although a complete picture of the temporal wave climate is not available through the observations presented herein, they do serve the purpose of providing nearshore wave data to validate the numerical models and once calibrated, the models can be used to simulate a wide range of seasonal situations and storm events based on longer term regional data.



Generally, wave energy was minimal during the deployment period, coinciding with summer conditions. However, a couple of time periods during the deployment had increased wave energy (June 1 and June 28, 2015). These two events were important for testing the accuracy of the wave model. Further discussion on the wave data and model application can be found in Appendix 5-A.

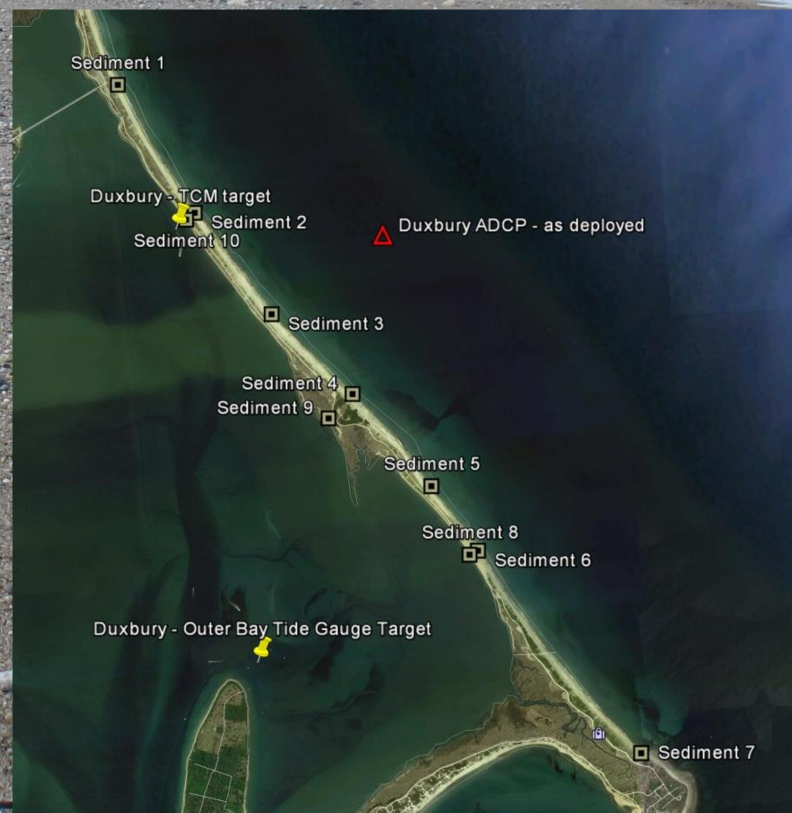
BEACH GRAIN SIZE

Sediment samples were taken along Duxbury Beach (both on the bay and ocean sides) to define the sediment distribution for the sediment transport modeling (Chapter 6). The results of the grain size analysis also provide insight on the local energy and/or sediment supply along the beach. For example, areas that have a higher percentage of coarser grain size material (gravel or cobble) are more likely to experience higher energy and/or have a reduced sediment supply. Along the ocean side of the barrier beach, and north of the High Pines drumlin, the beach is primarily poorly graded sand with sand percentages over 85%. On the ocean side of High Pines, the sediment becomes more a mix of gravel/cobble and sand, as the sand percentage drops to approximately 60%. South of High Pines, the ribbon of sandy beach returns (90% sand) until near the Gurnet Point drumlin, where the cobble reappears. On the bayside of the barrier beach, the sediment tends to be slightly coarser except in areas where existing or former salt marsh reside. These areas, for example the landward side of High Pines (sample site 9), consist of the finest material along the entire beach. Site 10 also has coarser grain material due to the introduction of cobble material used for the creation of a cobble berm.

Beach sediment sample taken at station 8 along Duxbury Beach. This sample was located on the bay side of the barrier beach and consisted of a sand and gravel mix. The median grain size was 1.6 mm.

Sediment Grain Size Analysis Results

Sample Site ID	D_{50} (mm)	Percent Sand	Classification
01	0.35	99.4	Fine Sand
02	0.30	88.5	Fine Sand
03	0.38	87.9	Fine Sand
04	2.03	59.8	Sand and Gravel
05	0.33	99.0	Fine Sand
06	0.40	90.5	Fine Sand
07	3.20	59.2	Sand and Gravel
08	1.60	52.1	Sand and Gravel
09	0.28	99.0	Fine Sand
10	0.72	69.2	Sand and Gravel



Location of Sediment Samples

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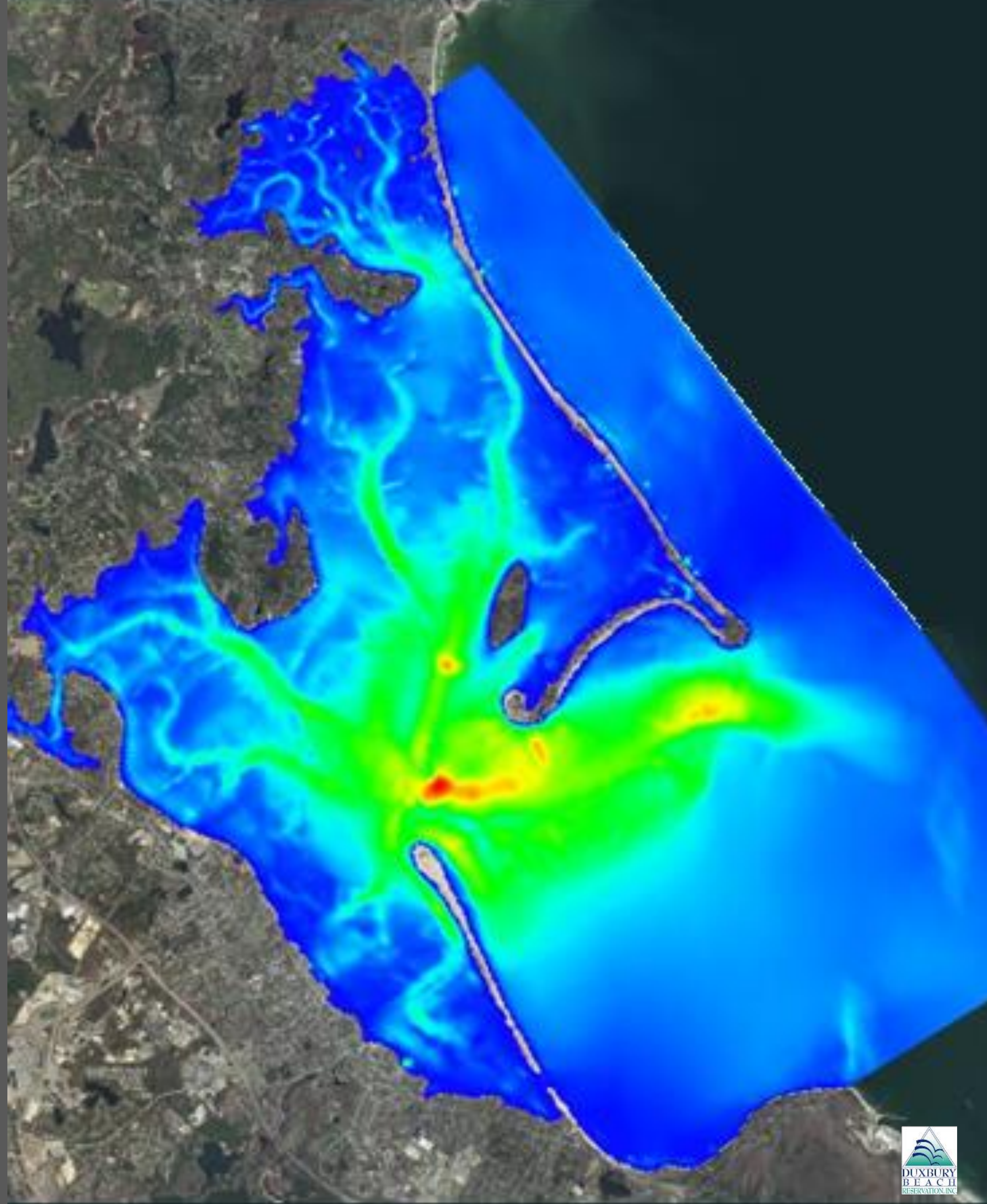
CHAPTER

4



HYDRODYNAMICS OF DUXBURY BAY

When considering erosion along Duxbury Beach, waves and storms attacking the barrier beach from the Atlantic Ocean is a primary driver; moving sediment offshore, driving it alongshore, and pushing it inland via overwash processes. Certainly this ongoing wave attack is a significant process in the evolution of Duxbury Beach. However, there is also erosion pressure that is caused on the bayside of the barrier beach due to tidally forced currents and wind-driven waves. Although not as dramatic as the erosion forces acting on the ocean side of the beach, these ongoing processes also work to shape the orientation and width of the barrier system. Therefore, when building resilience for Duxbury Beach, both the ocean and bayside of the barrier beach system needs to be considered.

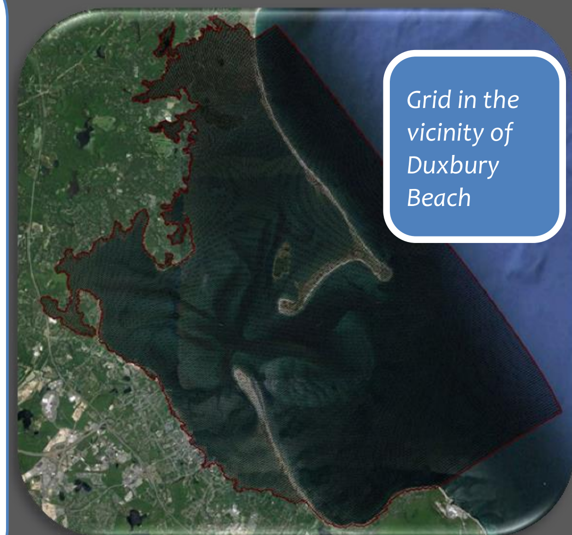
A hydrodynamic model was developed for Duxbury Bay to assess the tidal and storm induced currents within the bay and throughout the channels. While the hydrodynamic model used in this study was used to assess tidal currents, focusing on potential erosive influences on the backside of Duxbury Beach, the hydrodynamic model can also be used for numerous other purposes. For example, the model can be used to evaluate water quality, sediment transport patterns within the bay, tidal flushing, potential marsh restoration projects, potential dredging projects, impacts of various modifications to Duxbury Bay, and countless additional studies that would require the hydrodynamics of the Bay as baseline information. As such, this model is readily available for the Duxbury Beach Reservation or Town of Duxbury to use.

Duxbury Bay is a relatively shallow bay consisting of large tidal flats interspersed with many unsystematic tidal and navigational channels. A quantitative understanding of hydrodynamics is key to evaluation of ocean water circulation in Duxbury Bay. This chapter evaluates the hydrodynamic nature of Duxbury Beach and Bay. To quantify the tidal circulation system, site-specific water surface elevation and current conditions were determined using tide data, current data, topographic data, and a numerical hydrodynamic model. Hydrodynamic models provide predictive tools for evaluating various forces governing water surface fluctuations and water flows. This chapter focuses on the application and results of hydrodynamic modeling along the barrier shorelines and inside the Bay. A hydrodynamic model was used to drive the tidal current from offshore to the nearshore region and investigate potential changes to the flow field caused by the bathymetry and friction, while specifically evaluating the current velocities along channels adjacent to the bayside of the Duxbury Beach barrier. More details on the hydrodynamic modeling and assessment can be found in Appendix 4-A.

The development of the Duxbury Bay hydrodynamic model required configuration so that this particular application would best approximate the form and function of the real system. Model configuration involves compiling observed data from the actual estuarine system into the format required for the execution of the model. The first step in building the model is constructing the model grid. The grid is a digital abstraction of the prototype's geometry that provides the spatial discretization on which the model equations are solved. Different numerical methods require different types of grids, each having unique geometrical requirements.

The grid building process involves using geo-referenced digital maps or aerial photos to define the model domain and then generating the grid at the desired degree of spatial resolution within this domain. Elevation data are incorporated by interpolation of values to grid nodes or cells within the domain. For the EFDC (Environmental Fluid Dynamics Code) model (see details in Appendix 4-A), a structured grid is required. The accuracy of the model is highly dependent on accurate representation of the form of the real system expressed through the model grid. For Duxbury Bay, a curvilinear orthogonal grid was developed. While this type of grid is more difficult to implement, it allows for increased flexibility by allowing grid boundaries to better follow natural irregularities. The curvilinear orthogonal grid also allows gradual variation in horizontal resolutions, such that higher resolution areas can be defined in areas where greater detail is required. Higher resolution areas (smaller grid cells) are specified in regions of greater concern or complexity (e.g., geometric changes in the river, the navigation channels, etc.)

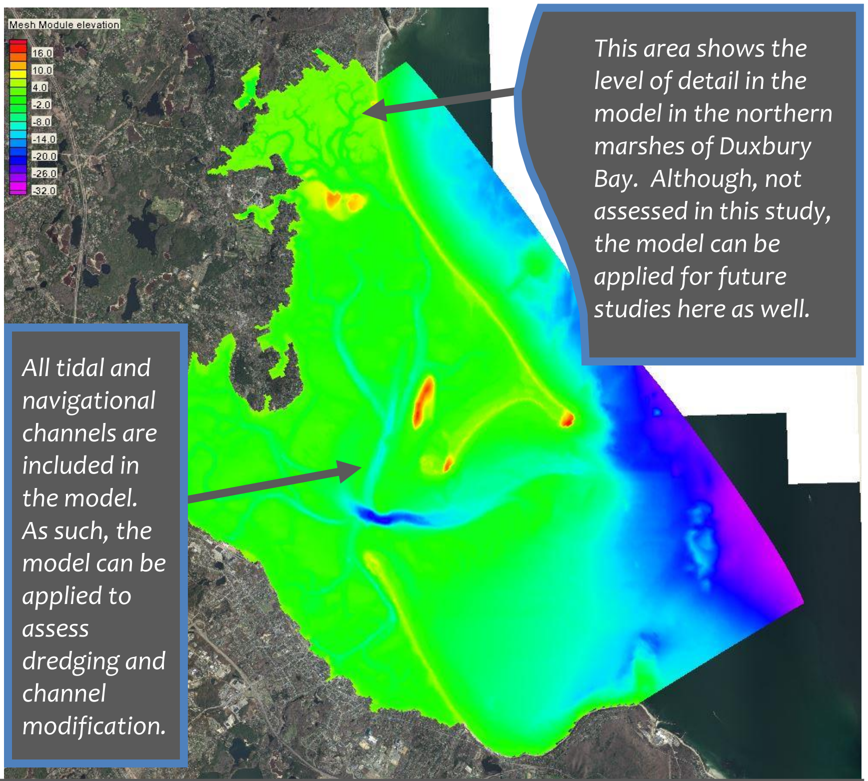
The model domain is represented by 61,655 grid cells, with cell dimensions ranging from 5 to 70 meters. Grid cells are shown as black lines. The high resolution of the model grid makes it difficult to identify individual grid cells within the model domain. The resolution of the model grid provides details on the hydrodynamics and mixing at a fine scale, allowing for accurate assessment of near- and far-field mixing.



Grid in the vicinity of Duxbury Beach

BATHYMETRY AND GRID GENERATION

Existing National Oceanographic and Atmospheric Administration (NOAA) hydrographic survey data were used to provide depth information for the hydrodynamic model. Nine (9) separate surveys were combined to define the entire region offshore Duxbury and within Duxbury Bay. In addition, US Army Corps of Engineers bathymetric data located within Duxbury Bay (from 2014) were used to provide more recent data in the vicinity of the navigation channel leading to the harbormaster facility. These are the same data used for the development of the wave model (Chapter 5). Additionally, topographic data for Duxbury Beach and the surrounding shorelines was obtained from MassGIS in the form of LiDAR (Light Detection and Ranging). These data were part of the 2011 Northeast coastal LiDAR data set.



This area shows the level of detail in the model in the northern marshes of Duxbury Bay. Although, not assessed in this study, the model can be applied for future studies here as well.

All tidal and navigational channels are included in the model. As such, the model can be applied to assess dredging and channel modification.

Water depths were interpolated to the grid cells from the combined bathymetric/topographic data sets. A color map, representing the water depths, shows the channels, the marsh detail, and barrier islands. Hot colors indicate higher elevations, while cooler colors are lower elevations.

MODEL CONFIGURATION

Once the model grid has been established, the model must be assigned boundary conditions in order to simulate the hydrodynamic conditions within Duxbury Bay. These boundary conditions consist of hydraulic parameters (e.g., water surface elevation, flow, etc.), atmospheric conditions (e.g., wind, precipitation, etc.), and coefficients (e.g., bottom friction). For the current study, which is focused on hydrodynamics, additional parameters are not implemented. However, in the future, the model can also be extended to include sediment parameters, water quality constituents, and other input parameters. For example, the model developed herein could be used by the Town of Duxbury or Duxbury Beach Reservation to evaluate various water quality parameters within the system or how sand migrates throughout the Bay. Key boundary conditions and model inputs are described below and detailed further in Appendix 4-A.

TIDAL BOUNDARY CONDITIONS

The driving force of the hydrodynamic model is the tides in the ocean. Hydrodynamic simulations of the Duxbury Beach and Bay included the specification of the water surface elevation at the eastern open boundary of the model domain. The ADCP water surface elevation data (Chapter 3) observed by Woods Hole Group was chosen as the tidal boundary condition for model calibration. Once calibrated, additional tidal boundary conditions were utilized to simulate other natural events and occurrences (e.g., storm surge etc.).

ATMOSPHERIC CONDITIONS

Wind (blowing over the water surface) and precipitation (directly falling on the Duxbury Bay) were assigned to model from local weather stations during the time of model calibration and instrument deployment. Rainfall totals were assumed to fall uniformly over the entire model domain, when applicable. Wind data were also applied evenly over the whole model domain. Once calibrated, these conditions can also be changed within the model to assess other natural events (e.g., large wind events, etc.).

FRESHWATER INPUT

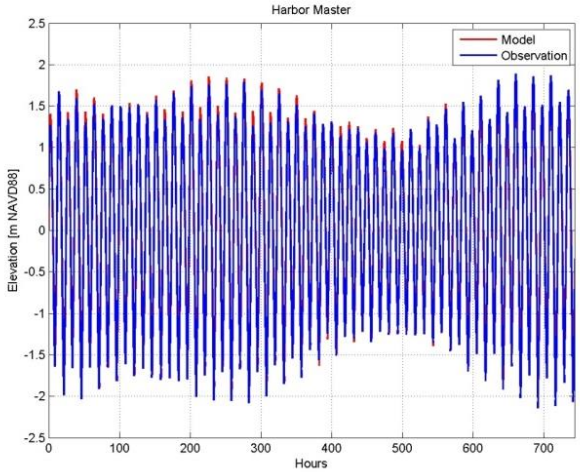
Freshwater input into Duxbury Bay comes from a combination of rainfall, direct runoff, and groundwater flow. Actual fresh water input rates vary in time and spatial distribution, and are difficult to measure. Directly measured data are not available during the time periods used for model calibration; however, estimates of freshwater inflow from a USGS groundwater model (Masterson, 2009) were used as a starting point for providing freshwater inflow. Additional freshwater inflow can be assigned to represent other natural events (e.g., precipitation).

BOTTOM ROUGHNESS

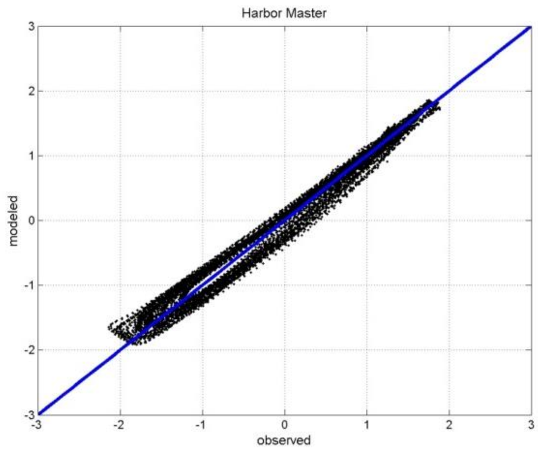
Bottom roughness (or the friction the seafloor induces on the water flow) was varied throughout the model domain in order to provide the best match to the measured data in the system (see model calibration). The value of the bottom roughness height ranged from 0.4 inches for tidal flats to 4 inches for overland areas.

Type	*(in)*
Tidal flat	*0.4*
Open water	*0.8*
Channels	*0.8*
Marsh	*2.4*
Barriers	*3.2*
Land	*4.0*

MODEL CALIBRATION



Visual comparison of the modeled water surface elevation results (red line) with the observed water surface elevation results (blue line) shows good agreement. This figure shows the comparison at the Harbormaster station. Water surface elevation is shown on the vertical axis (meters, NAVD88), while time is shown on the horizontal axis (hours).



Scatter plot of calibration results at the Harbormaster station. If the modeled data mimicked the observations exactly, every dot would lie on the blue line. Results show favorable comparison of the modeled and observed water surface elevations. These comparisons were made at every measurement location.

Statistical results of water surface elevations calibration.

Upper Marsh		Harbor Master		Clarks Island	
ME (ft)	RMSE (ft)	ME (ft)	RMSE (ft)	ME (ft)	RMSE (ft)
-0.17	0.146	-0.02	0.150	-0.15	0.131

Approximate average peak velocities in channel location during spring and neap tides. The model slightly under predicts spring velocities, and slightly over predicts neap velocities.

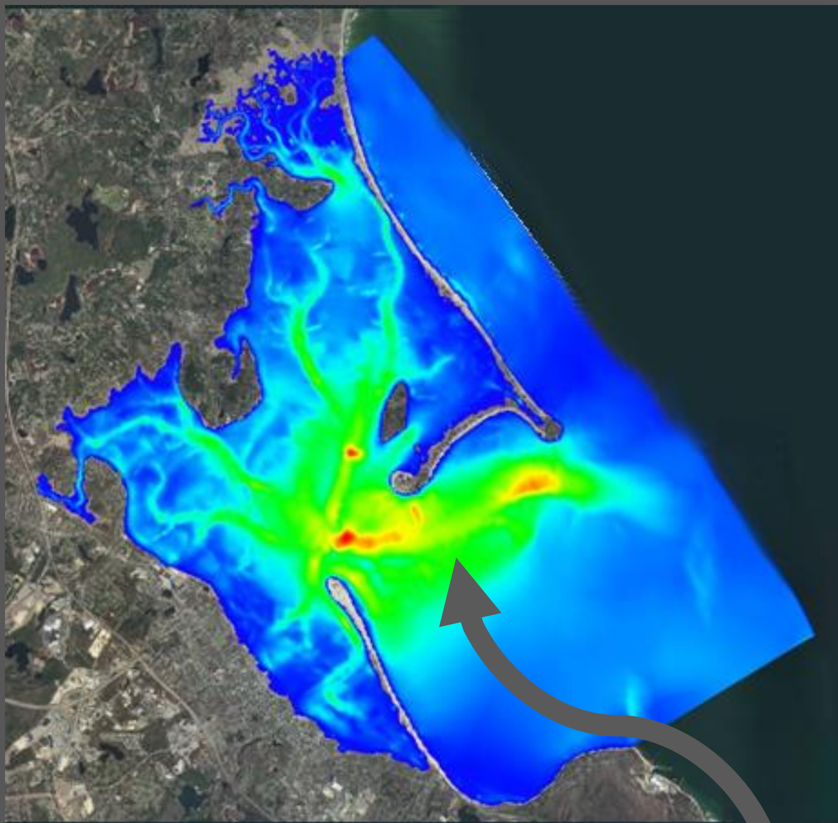
Spring Tides		Neap Tides	
Model (cm/s)	Data (cm/s)	Model (cm/s)	Data (cm/s)
43	49	26	21

After establishing the grid, boundary conditions, input conditions and model coefficients, the model can be applied to simulate water surface elevations, currents, salinity, and temperature at every node within the model domain. However, prior to using the model to simulate various conditions, the model must be calibrated. Model calibration is the process by which adjustments are made to the model parameters to ensure the model appropriately simulates measured water surface elevation, velocities, salinity, and other observed parameters. This requires conducting a series of iterative model simulations to ensure the model is stable, and results compare favorably with measured data. Calibration can be a lengthy process involving hundreds of model simulations where model coefficients are adjusted (within acceptable ranges) until the modeled water surface elevation, salinity, and temperature closely approximate the measured field observations. For this particular project, water surface elevations, measured during this time period at Clarks Island, Harbor Master, and Upper Marsh locations (Chapter 2), were used as calibration points within the model domain. The model was then simulated and calibrated for a selected 30-day time period (June 5th through July 5th 2015). The calibration focused on the water surface elevations observed in Duxbury Bay. The water surface elevation measurements were crucial to predicting the correct hydrodynamics.

The overall performance of the model was determined by comparing the time series of observed data with the modeled data. Visually, the model results compare well to the data observations, for both amplitude and phase at these three locations. In addition to the visual comparison, the observed and modeled data were compared through statistical error analysis. Error statistics were computed to quantify the performance of the hydrodynamic model during the calibration period. For example, the mean error (ME) and root-mean-square error (RMSE) were two of these error statistics calculated. The ME is a measure of the average deviation of the simulated values from the observed values. A positive value means, on average, the model is over predicting, while a negative bias means the model under predicted the results. The performance of the model can also be evaluated using the RMSE value. The smaller the RMSE value, the better the model performed. The water surface elevation comparison shows mean errors of approximately 5 centimeters or less and RMSE approximately 17 centimeters or less during the calibration time period. The visual comparisons and error statistics both show reasonable agreement between the measured and modeled water surface elevation results.

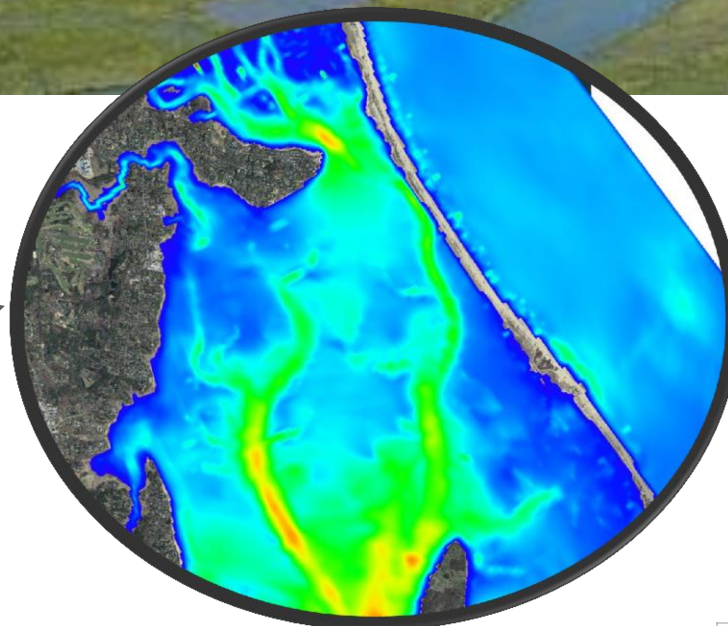
The model was also validated to the current observations within Duxbury Bay (Chapter 2). Validation involves applying the calibrated model to set of observed data that are independent from the calibration data set without changing the model configuration or parameterization. The comparison of measured to modeled velocities also shows reasonable agreement. Further details on model calibration are presented in Appendix 4-A.

NORMAL TIDAL CONDITIONS



Following model calibration, simulations were performed for the typical, normal tidal conditions to evaluate water surface elevations, circulation patterns, and velocities within Duxbury Bay. Outputs of water surface elevation and current velocity were assessed every hour over typical neap and spring tidal cycles. Then maximum values of water surface elevation and velocity were calculated for the entire time domain. There was minimal tidal attenuation throughout the bay, indicating that, in general, tidal flushing is high. Changes in water surface elevation were apparent in some of the more remote areas of the bay, such as the northern salt marsh regions. Velocities throughout the bay were much more variable, with maximum currents occurring in the vicinity of the entrance to Duxbury Bay, as well as intensification of currents in the channels and navigational waterways compared to the tidal flats.

Maximum current velocities throughout the model domain for normal tidal conditions. Maximum current speeds exceed 4-5 feet per second in the entrance to Duxbury Bay. Greens, yellows, and reds indicated swifter velocities, while blues indicate lower velocities. Additional details can be found in Appendix 4-A.



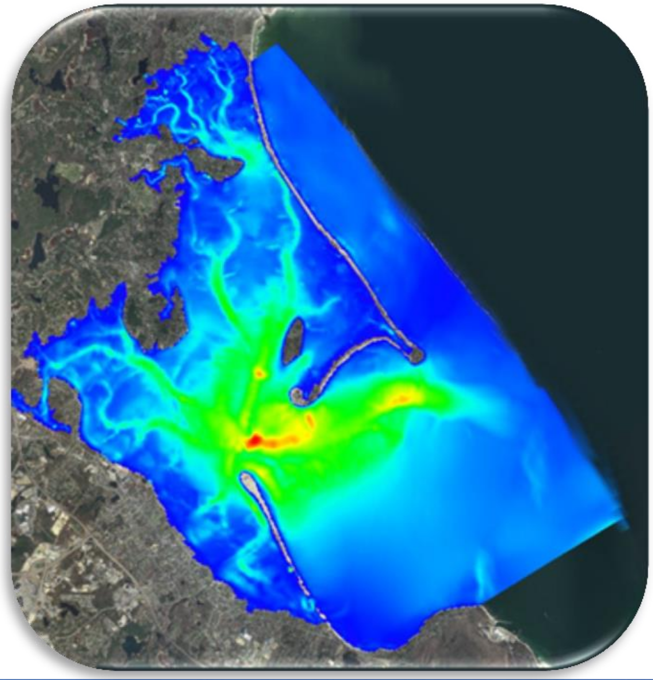
Maximum current velocities occurring in the northern section of Duxbury Bay for normal tidal conditions. Results illustrate the swifter currents (greens and yellows) that follow the existing channel configuration. Maximum velocities in the channels are approximately 2-3 feet per second faster than other locations throughout the bay.

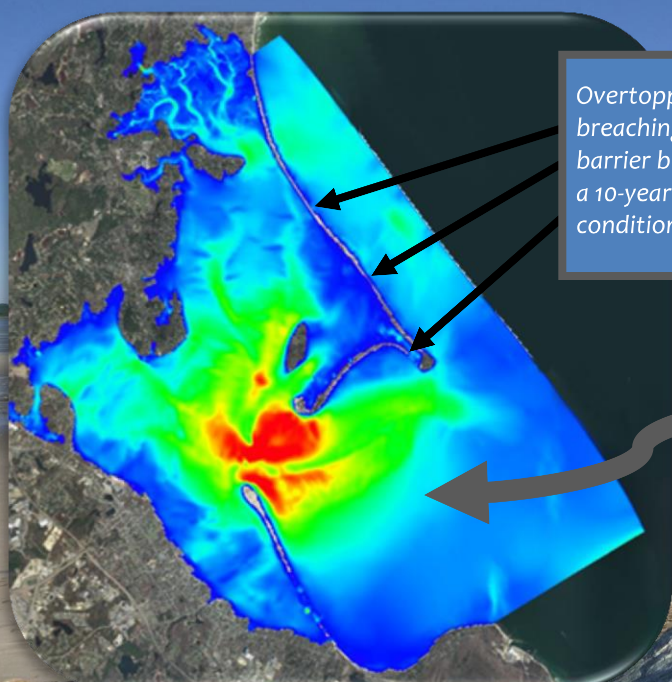
STORM EVENTS AND SEA LEVEL RISE

The hydrodynamic model was also used to simulate high energy storm events for return-period storms. 10-, 50-, and 100-yr return period storms conditions were simulated by combining storm surge values with the normal tide. The storm events were set up for 6-day long simulations and water surface elevations and current velocities were evaluated throughout the system. The maximum current velocity fields do not show much difference among the 3 storm events, but do produce larger velocities than normal tidal conditions. Overall, the storms also result in much larger maximum water surface elevations, as expected.

Return Period Storm	Surge Elevation (ft, NAVD88)
10-year	8.1
50-year	9.1
100-year	9.5

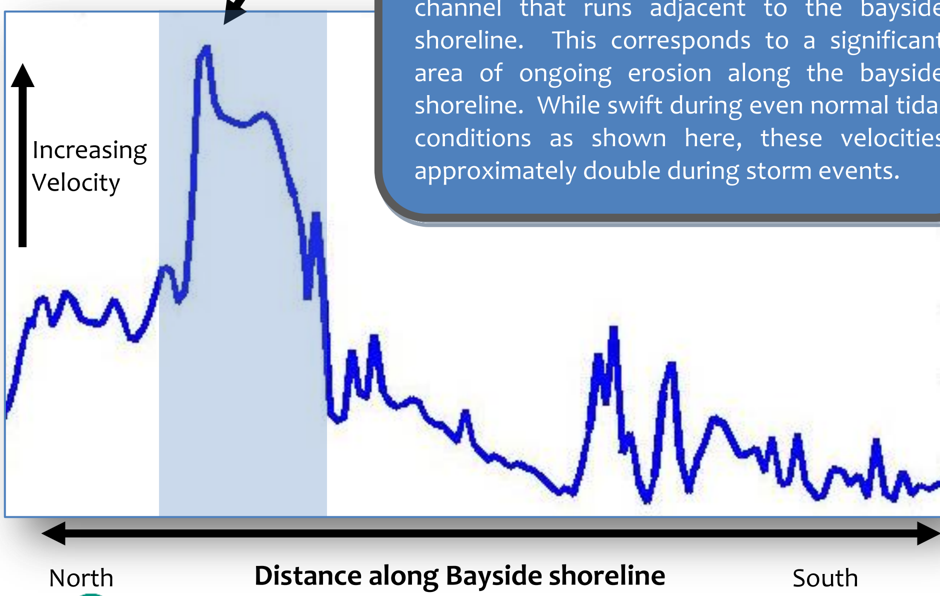
Peak velocities throughout Duxbury Bay during a 50-year return period storm event. Maximum velocities are increased compared to normal tidal conditions, ranging from a 20% increase in velocity at the inlet, to 50-60% in some of the tidal channels.





Overtopping and breaching of the barrier beach under a 10-year storm condition in 2065.

Another important consideration in the hydrodynamic simulations, as well as the long-term planning for Duxbury Beach, is potential sea-level rise. The potential impacts of sea-level rise (SLR) present an additional natural hazard risk for developed areas within the coastal zone, as well as influencing the resiliency of Duxbury Beach. In order to assess the potential impacts of projected sea level rise on the hydrodynamics of Duxbury Bay, as well as the resiliency of the barrier beach, a number of simulations were conducted with projected sea level rise in 2065 (2.87 feet increase based on National Climate Data high projections). For one case, this SLR condition was combined with a 10-year return period storm to assess what a moderate storm may look like in the future. This results in overtopping of the barrier beach in certain areas, as well as increased velocities, especially in the inlet to Duxbury Bay. Further details on the development of this scenario can be found in Appendix 4-A and 6-B.



Peak velocities are significantly higher in the channel that runs adjacent to the bayside shoreline. This corresponds to a significant area of ongoing erosion along the bayside shoreline. While swift during even normal tidal conditions as shown here, these velocities approximately double during storm events.

While the overall circulation within the bay is important to understand and is useful for many other applications and studies, the focus of this evaluation was the potential impacts of the circulation within Duxbury Bay on the overall resiliency of the barrier beach system. As such, an important component of the hydrodynamic modeling effort was the assessment of the tidal and storm velocities that occur along the bayside shoreline of Duxbury Beach. The model was used to assess these conditions, specifically in the tidal channel that has migrated east and runs directly adjacent to the bayside shoreline. The velocities in this channel are significantly higher than along the rest of the bayside shoreline and are a primary contributor to the erosion that has developed in this area (e.g., this area has been protected with a cobble berm project). This condition creates a narrower overall beach width as greater erosion potential exists on both the bay and ocean side of the barrier beach. This leads to a weaker shoreline in this region, which may be more prone to overwash and potential breaching.

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CHAPTER 5

WAVES AT DUXBURY BEACH

WOODS HOLE GROUP

DUXBURY BEACH RESERVATION, INC.

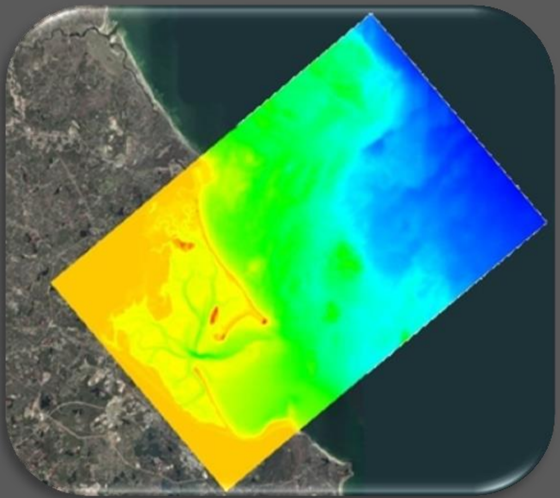
ANALYSIS APPROACH

In order to evaluate local sediment transport pathways, as well as assess and identify potential alternatives to mitigate erosion and build resiliency at Duxbury Beach, an understanding of the regional wave climate is required. Wave transformation modeling allows for simulation of refraction, diffraction, shoaling and breaking of waves at the regional and local level. Both refraction and diffraction have a significant impact on how waves influence the shoreline. Wave refraction and diffraction produce an uneven distribution of wave energy along the coast and control sediment transport in the region. Wave modeling allows for quantitative predictions of these processes.

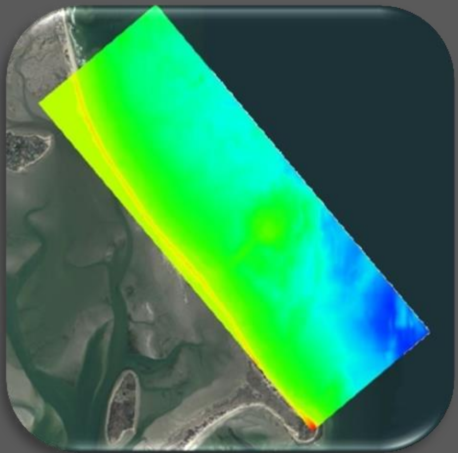
Ocean wave energy is comprised of a large variety of waves moving in different directions and with different frequencies, phases, and heights. These waves undergo significant modifications as they advance into the coastal region, interact with the sea floor, and eventually reach land. The ocean climate also changes temporally with seasonal modulations. The variability in offshore wave climate, the transformations occurring as waves propagate landward, and the temporal modulations, all result in significant fluctuations in the quantity and direction of sediment transport in the coastal zone. Therefore, in many cases, using a single representative wave height, frequency, and/or direction is not the most accurate technique for assessment of wave climate, and subsequently, the sediment transport at the coastline. As such, a spectral wave model was used to propagate random waves from offshore to the nearshore region and investigate potential changes to the wave field.

This chapter presents results of the wave climate analysis offshore the eastern coast of Duxbury Beach and the transformations waves experience as they propagate towards the coastline. To quantify the wave impact along Duxbury Beach, site-specific wave conditions were determined using wind data, wave data, and a numerical wave transformation model. Wave transformation models provide predictive tools for evaluating various forces governing wave climate and sediment transport processes. Wave modeling results provide information on wave propagation across the continental shelf and to the shoreline, revealing areas of increased erosion ("hot spots of energy"). The refraction and diffraction mechanisms also result in changes in the offshore wave direction that may significantly influence the rate and direction of sand movement. Therefore, the quantitative information provided from the numerical model can be used to explain the physical processes that dominate a region and to furnish appropriate recommendations/solutions for each location along the coast. More details on the wave transformation modeling and assessment can be found in Appendix 5-A.

The wave transformation model requires a grid consisting of a mesh of points. At each point within the domain, water depth, as well as ambient current data, is specified. Reference points are separated by spacing in the alongshore and cross-shore directions. The model domain encompasses the entire shoreline of Duxbury Beach. Due to the large region simulated, as well as the high level of detail required in the nearshore region, nested grids were specified. As such, the larger regional grid propagates the offshore waves from the ocean into the Duxbury Beach area, then the smaller, higher resolution model provides details on the wave processes directly along Duxbury Beach. The grid nesting approach allows for accurate wave transformations from the offshore region to the nearshore region, and provides high-resolution wave information in the active zone of sediment transport. The color shading is representative of the depth in the model, assigned from the bathymetric source data. Blue and green colors represent deeper water, while red and yellow colors represent shallower water.



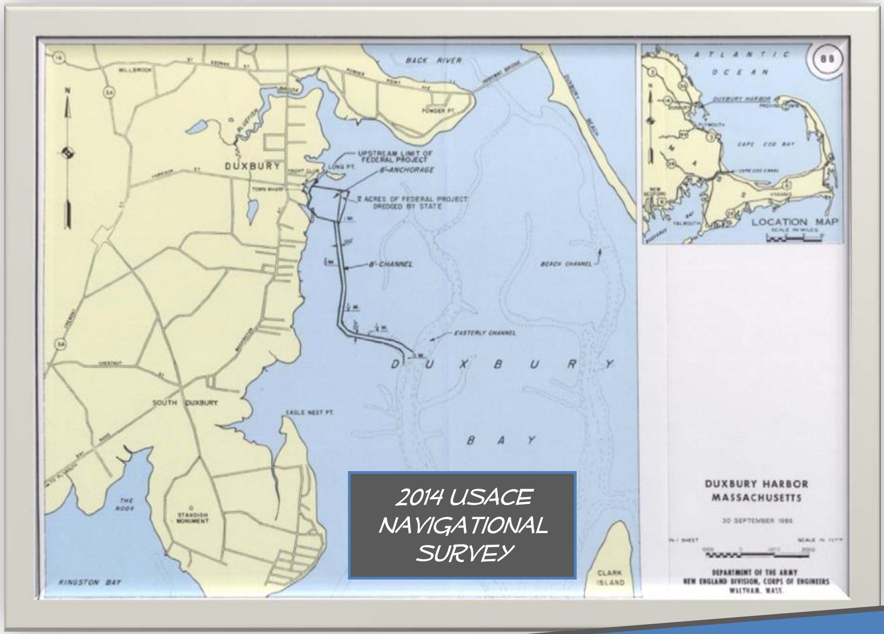
The regional, offshore grid is comprised of 506 cells in the cross-shore direction and 330 cells in the alongshore direction at a resolution of 50 m (165 ft). The offshore boundary of the regional grid is at approximately the 55-meter (180 ft) depth contour.



The nearshore grid was created to obtain better resolution in the nearshore region for sediment transport modeling. The local, nearshore grid consists of 498 cells across the shore and 1382 cells along the shore with a resolution of 5 meters (16 ft).

BATHYMETRY AND GRID GENERATION

Existing National Oceanographic and Atmospheric Administration (NOAA) hydrographic survey data were used to provide depth information for the wave model. Nine (9) separate surveys were combined to define the entire region offshore Duxbury and within Duxbury Bay. In addition, US Army Corps of Engineers bathymetric data located within Duxbury Bay (from 2014) were used to provide more recent data in the vicinity of the navigation channel leading to the harbormaster facility. These are the same data used for the development of the hydrodynamic model (Chapter 4).



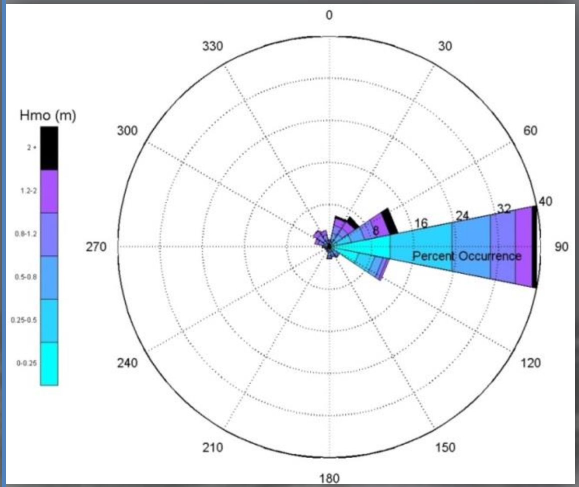
The orientation of the reference grids, especially the offshore boundary, was selected to closely represent a shore parallel contour line at a water depth deep enough that waves would not sense the sea floor, and align with the location of the offshore wave information. The reference grids were rotated to be oriented perpendicular to the shoreline, such that a comprehensive range of directional approaches could be simulated. Rotation of the grid allowed for simulation of all wave approach directions for the Duxbury Beach shoreline (waves arriving from -50 to 130 degrees relative to true North).

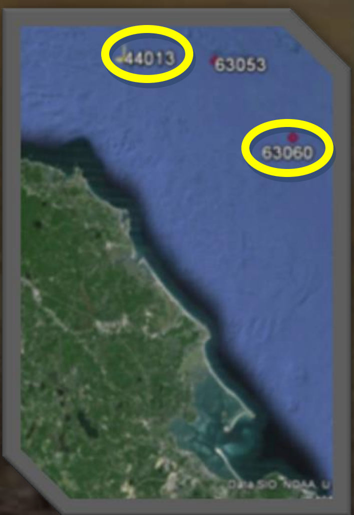
WAVE CLIMATE

Transformation wave modeling can only be as accurate as the input data; therefore, a key component of accurate wave modeling is the analysis and selection of input wave data. The results derived from numerical wave transformation modeling, as well as the subsequent movement of sediment in the coastal zone, are controlled by the selected wave input conditions. Assessment of the offshore wave climate and selection of input wave parameters requires determination of average annual and storm conditions.

Long-term time series of wave climate are not available for most shorelines because wave gages are expensive to install and maintain and are often temporarily out of service for maintenance or repair. For Duxbury Beach, in addition to the short-term nearshore wave data collected as part of this project, two different types of time series wave data were used: National Data Buoy Center (NDBC) and US Army Corps of Engineers Wave Information Study (WIS) data.

The distribution of significant wave height (illustrated using a wave rose plot) for WIS station 63060. The colors indicate the magnitude of the wave height, the circular axis represents the direction of wave approach (coming from) relative to True North (0 degree), and the extending radial lines indicate percent occurrence within each magnitude and directional band. The primary clustering of wave directions tends to arriving from the east (90 degree), with higher energy events from the northeast.





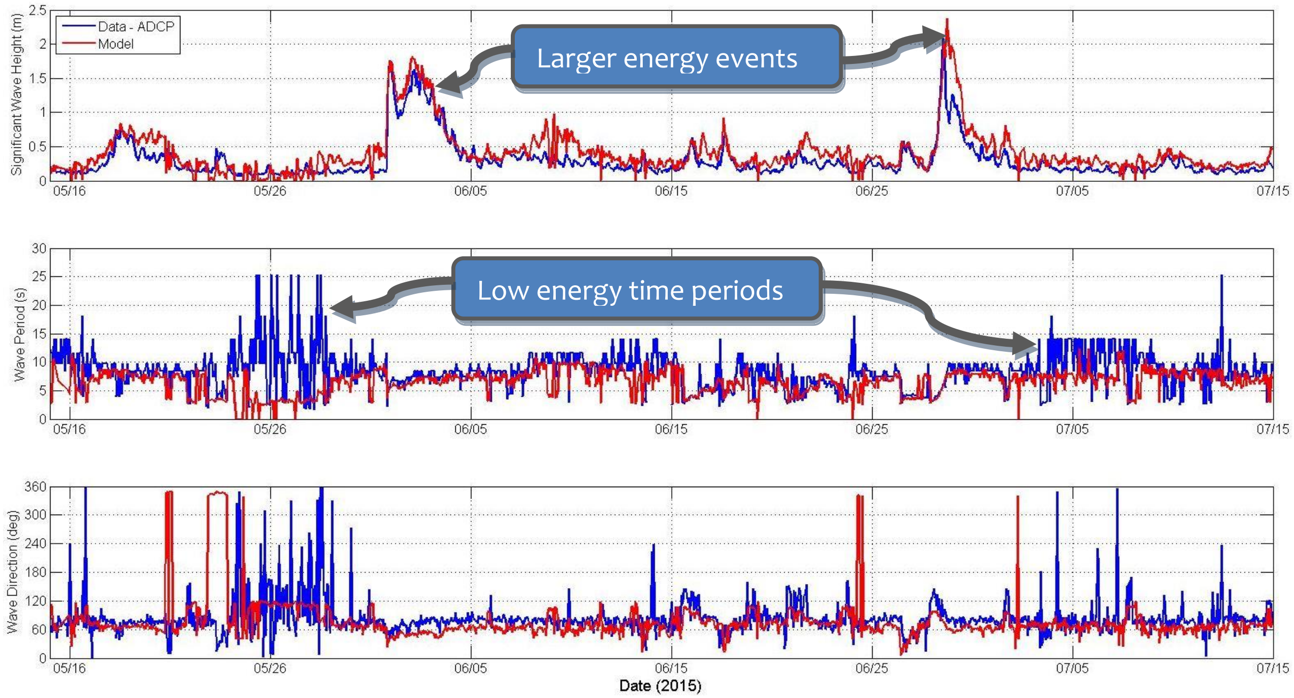
Station	NDBC 44013	WIS 63060
Latitude	42.35°N	42.25°N
Longitude	70.65°W	70.50°W
Depth (m)	64.5	56
Time Period (yrs)	1986-2015	1980-2012

NDBC station (44013) in Massachusetts Bay was selected based on the water depth and distance offshore, which are similar to the ocean boundary of wave model domain. WIS station (63060) in Massachusetts Bay was selected to represent the ocean boundary of the wave model domain based on its location and physical parameters. These are also the closest stations to Duxbury Beach.

Both the NDBC and WIS stations provide long-record time series wave data (30 years and 33 years, respectively), which were used to provide offshore wave boundary conditions. The NDBC buoy wave data were used to validate the model performance through comparison to the nearshore wave data measured by Woods Hole Group in 2015. Additionally, the 33-yr WIS data set offers a synopsis of the wave climate offshore of Duxbury Beach and was used to produce annual average wave conditions. As such, these data led to the development of appropriate input spectra and identify the variability in wave approach and the potential impacts on sediment movement. In order to develop the annual average wave conditions, a detailed analysis was conducted to summarize existing WIS data into detailed input spectra. Each spectral simulation contains distinct differences in energy or directional spectra, and consequently produces varying impacts in the wave transformation and sediment transport patterns. Full details are presented in Appendix 5-A.

Prior to using the model to transform long-term wave climate information into the Duxbury Beach region, the wave transformation model must be validated to ensure adequate performance. The entire time period (May 14 to July 15, 2015) the nearshore wave ADCP was collecting data was simulated for model validation. The hourly NDBC observation data at Station 44013 were downloaded for the entire deployment time period. The wave parameters, including wave height, wave period, and wave direction, were used to generate the spectral energy distribution in the frequency and direction domains. These wave spectra were defined as the input wave conditions at the open ocean boundary. Wave model results were compared to the wave measurements from the nearshore ADCP station to verify the performance of the model.

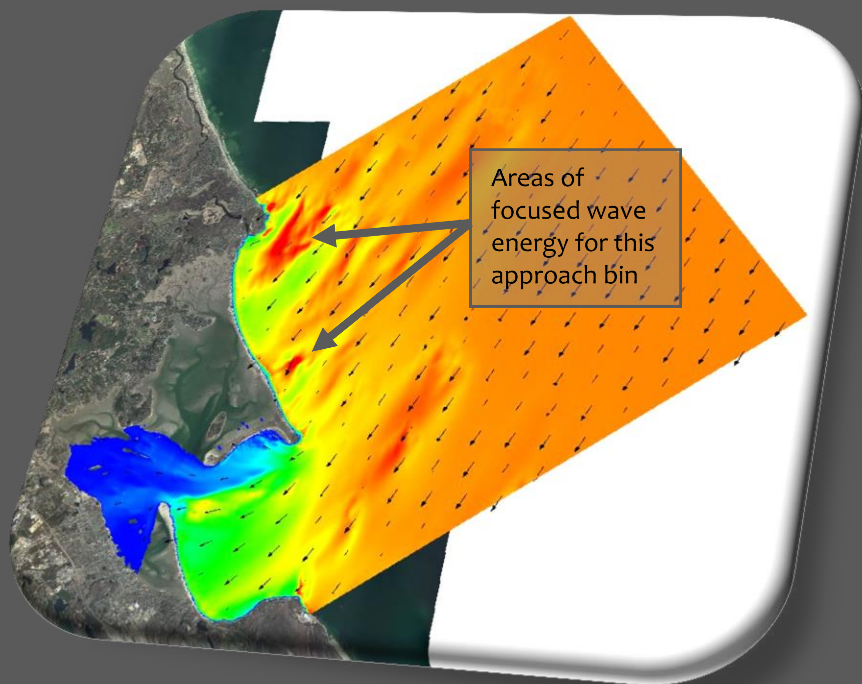
Comparisons of the modeled (red) and measured (blue) wave heights, wave periods, and wave directions for the two-month period when the nearshore ADCP was measuring wave conditions were conducted. A wave direction of approximately 40 degrees represents waves approaching normal to the shoreline. Visually, the wave model compares favorably to the observations, and is able to accurately simulate specific wave and storm events, as well as calm periods. Both average and storm conditions are well represented throughout the simulation time. For example, both large events in May and June are accurately predicted. The wave model does a reasonable job of predicting the changes in the wave field due to the transformations from offshore to nearshore. Once validated, the model can be extended to simulate a wide range of conditions, including longer time periods and storm events.



The key for wave model validation is adequate prediction of the wave components (height, period, and direction) when the sea state has wave energy (e.g., waves are actually present). Calm sea states, or times of low energy, have highly variable wave periods and directions since there are no waves to measure. These appear in the time series record as unresolved values. In other words, there needs to be at least some wave energy for the instrument to identify waves. The model should not match the period and direction observations during these low energy time periods since there are no waves. The model does a reasonable job of predicting the sea state when there is wave energy.

AVERAGE ANNUAL CONDITIONS

Example regional grid wave transformation results for the North-Northeast direction approach bin. Reds and yellows show areas of higher wave heights, while blues and greens show lower wave heights. . Arrows indicated the wave direction. Complete results for both regional and local subgrids are shown in Appendix 5-A.

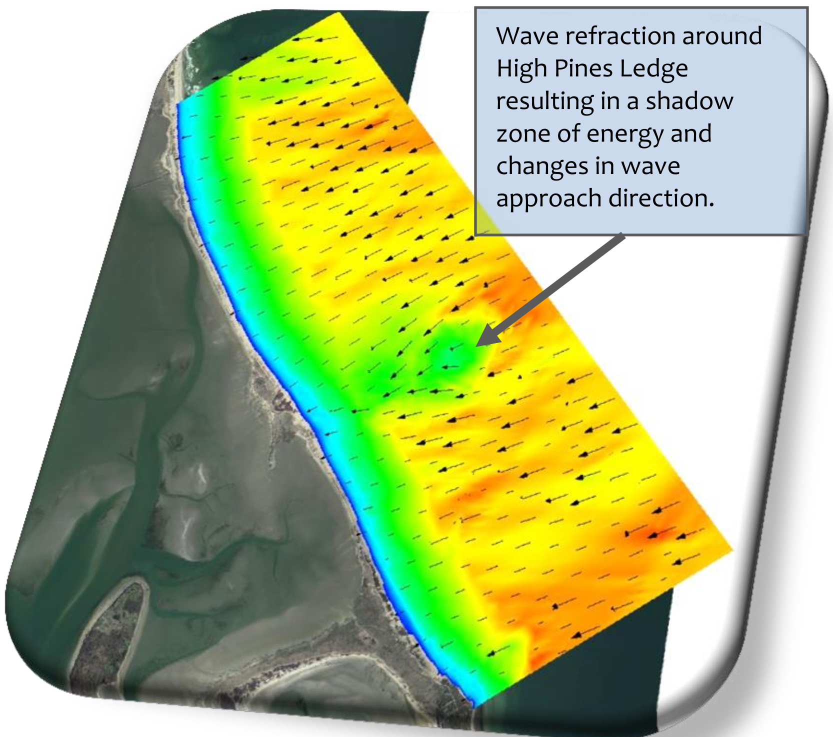


The wave model requires input of a directional wave spectrum, which represents the distribution of wave energy in the frequency and direction domains. In order to determine long-term wave conditions and wave statistics at the coastline, as well as for use in sediment transport calculations, spectral data from WIS Station 63060 were used to derive energy-conserving annual average directional spectrum. Wave data were segregated by direction of approach, and an energy distribution, as a function of frequency, was generated from all the waves in each directional bin. The energy associated with each frequency was then summed to create an energy distribution for each approach direction. In essence, a representative two-dimensional spectrum was generated for each approach directional bin based on the sum of all the WIS spectra approaching from that mean direction. This was then combined with the percentage of occurrence to create a long-term evaluation of wave impacts at the shoreline. This energetic directional bin approach identifies all potential approach directions, including those that may occur only a small percentage of time during a typical year, but potentially have significant impacts on the shoreline and sediment transport. For example, larger waves come from North and Northeast directions, while more commonly occurring waves come from the East.

Directional Bin (0°=N)	Approach Direction	Percent Occurrence	Sig. Wave Height (ft)	Peak Period (sec)	Peak Direction (0°=N)
303.75 to 326.25	NW	3.74	3.14	4.9	315.3
326.25 to 348.75	NNW	3.24	3.18	5.4	337.3
348.75 to 11.25	N	3.30	3.14	6.3	0.3
11.25 to 33.75	NNE	4.21	3.44	6.8	23.2
33.75 to 56.25	NE	6.89	3.94	7.6	46.0
56.25 to 78.75	ENE	13.10	3.41	9.0	69.9
78.75 to 101.25	E	38.54	1.94	9.0	90.6
101.25 to 123.75	ESE	10.90	1.38	8.4	107.1
Calm	--	16.08	--	--	--

Cases were simulated to represent the complete wave climate offshore of Duxbury Beach. This consisted of directional bins with associated percent occurrence, significant wave height (mean wave height of the highest third of the waves), peak period (the period associated with the most energetic waves), and peak direction. The frequency and directional energy spectra were tailored to match the energy distribution of each approach bin occurring in the WIS data. Therefore, the directional and frequency distributions matched the data directly. Only waves propagating towards the coast were simulated. Waves headed offshore represent a calm period along the coastline.

Example local subgrid wave transformation results for a 50-year return period storm. Reds and yellows show areas of higher wave heights, while blues and greens show lower wave heights. Arrows indicated the wave direction. Complete return period storm results for both regional and local subgrids are shown in Appendix 5-A.



HIGH ENERGY EVENTS

Since high-energy events have a significant impact on many physical processes (and in most cases, dominate erosion), it is crucial to include storm simulations in wave modeling to assess the potential impact of a storm on the shoreline and the potential sediment transport along Duxbury Beach. High energy events were evaluated by reviewing the 33-year wave hindcast at WIS station 63060. A return period analysis was completed by the US Army Corps of Engineers for storm events that exceed wave height larger than 6.5 feet. From this analysis, wave conditions for 10-year, 50-year, and 100-year return period storms were developed for Duxbury Beach. Since the wave direction of potential return period extreme events is unknown, a mean wave direction was calculated from all WIS data storm events. This direction was chosen to represent the wave direction for all return period synthetic storms.

Storm surge values were also included in the wave modeling simulation to represent the increased water level experienced during the passage of a large storm event. Elevated water levels, even with moderate wave heights, can result in significant erosion along the shoreline. Storm spectra were developed from these storm parameters using standard parametric methods, since the observed spectra during these events are unknown. These input conditions were then used to simulate return period storms in the wave transformation model.

Wave parameters used to develop high energy wave event conditions.

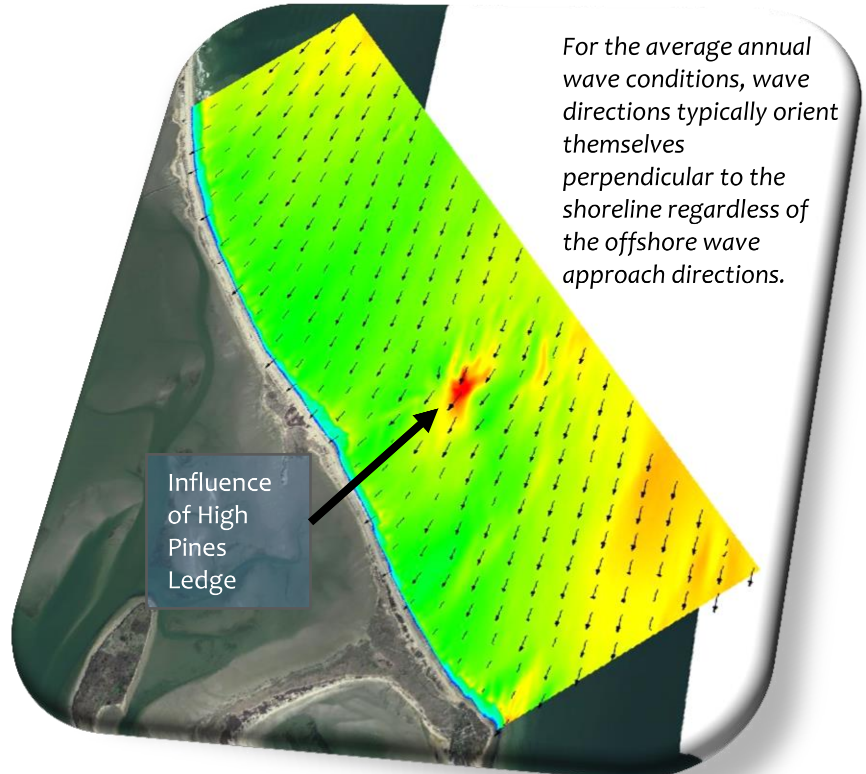
Event	Storm Surge [ft_NAVD88]	Offshore Wave Height [ft]	Wave Period [sec]	Wave Direction [0°=N]
10-Year	8.1	21.3	12.0	55.4
50-Year	9.1	26.2	13.3	55.4
100-Year	9.5	28.2	13.8	55.4

Sea level rise conditions, as presented in Chapter 4, were also used to evaluate wave conditions that may occur under a changing climate. These climate change modeling results were utilized when evaluating the performance of the resiliency options (Chapter 6 and 7). For example, the effects of a 10-year storm event in 2065 were evaluated compared to a 50-year storm in 2015.

WAVE SUMMARY

Wave model simulations were performed for the typical wave conditions represented by directional bin spectra that describe the annual average wave climatology offshore of Duxbury Beach. Wave transformations occur as the waves propagate from offshore towards the barrier beach and eventually collide with the coastline. Waves converge and diverge at several locations throughout the modeling domain (Appendix 5-A), which results in variations in the wave energy propagating towards the Duxbury coastline for each directional bin. Bands of increased wave energy are apparent throughout the region, which vary based on the approach wave directions. Each directional bin has an associated percent occurrence, which indicates the frequency of those wave conditions. The High Pines Ledge has a consistent influence on the wave energy along Duxbury Beach. In all approach directions, High Pines Ledge significantly influences the wave directions and heights impacting the shoreline. This ultimately plays a role on the sediment transport patterns landward of the ledge. The variability in the wave climate is clearly indicated by the differences in nearshore wave patterns arising from the various input spectra approach directions. The combination of all the directional approach cases allows for an assessment of the average annual wave climate, and can be used to generate wave-induced currents and regional sediment transport. The results of all the approach directions are used, in concert with the percent occurrence, to compute the annual sediment transport in the region (Chapter 6.0).

The wave transformation model was also used to simulate high energy events. The simulation of specific return period storm events was important to quantify the short-term impacts that occur during these energetic scenarios. Sediment transport along the coastline in many cases can be dominated by these short episodic events. Wave heights are significantly higher than during the annual average directional cases, as the offshore heights are in excess of 21.3 feet in locations. The storm event spectral results, as were the annual average directional bin cases, were passed forward to the local scale transformation model to assess direct impacts on the Duxbury Beach region.



For the average annual wave conditions, wave directions typically orient themselves perpendicular to the shoreline regardless of the offshore wave approach directions.

Waves coming from the north, (shown here by the black arrows) refract such that at the shoreline waves generally approach perpendicular to the coast. The figure shows results from the nearshore subgird.

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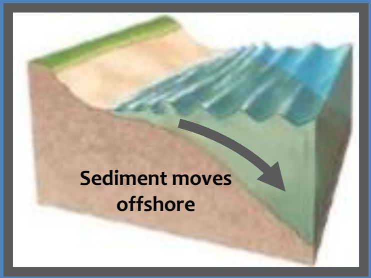
CHAPTER 6

SEDIMENT TRANSPORT ON DUXBURY BEACH

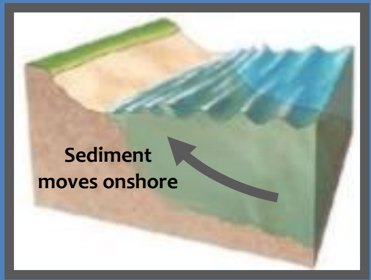
ANALYSIS APPROACH

CROSS-SHORE SEDIMENT MOVEMENT

HIGH ENERGY WAVES



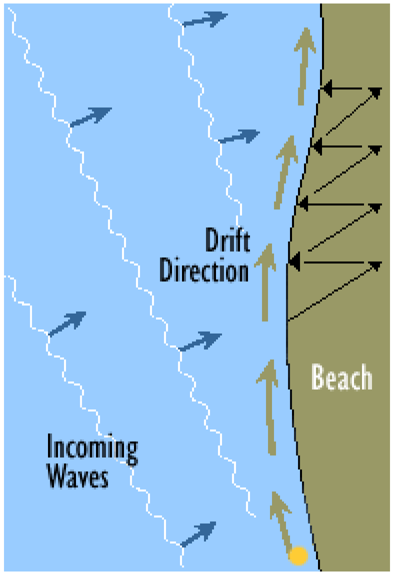
LOW ENERGY WAVES



The cross-shore (or onshore and offshore) movement of sediment at a beach is most significantly influenced by the level of wave energy acting on the shoreline. During lower energy wave periods (e.g., summer conditions), net cross-shore sediment movement is directed onshore. However, when the beach experiences high energy waves (e.g., storms, winter conditions), the net cross-shore sediment movement is directed offshore. Additionally, for barrier beaches, such as Duxbury Beach, storm events can overtop the barrier beach and drive large volumes of sediment landward in overwash plains.

ALONGSHORE SEDIMENT MOVEMENT

The along shore movement of sediment at a beach is influenced by the energy and direction of the approaching waves, as well as a number of other factors (grain size, beach slope, wave steepness, etc.). Incoming waves induce nearshore currents and create wave swash on the beach. The creation of these nearshore currents and the intertidal swash zone produce sediment movement along the beach. While the direction of waves and current movement changes throughout the year, resulting in changes in the direction and rate of transport; ultimately there is a dominant net direction that occurs due to the dominant wave transformations. This produces the net alongshore transport rate.



Understanding the wave transformations (Chapter 5) is a critical step in the determination of shoreline processes and changes, and this wave information is required in order to provide an estimate on how sediment moves in the nearshore region. The wave modeling results were the key input into the sediment transport modeling and beach performance evaluation presented in this Chapter and in Chapter 7. The goal of the numerical sediment transport models are to provide a physically-based representation of alongshore currents and sediment transport driven by breaking waves in the surf zone. The specific objective is to obtain estimates of the alongshore sediment flux integrated across the surf zone, as well as estimates of cross-shore flux during higher energy wave events. As such, this chapter evaluates the regional sediment transport for Duxbury Beach in the alongshore direction, and site-specific assessments of cross-shore sediment movement. The sediment transport modeling is also used to determine the performance of various alternatives presented and evaluated in Chapter 7.

Sediment movement in the coastal zone can be estimated by using various types of sediment transport models and/or equations. These models may differ in their detail, in their degree of representation of the physics, in their complexity, and in other manners. Process-based sediment transport models (those that directly address the fundamental physics of waves, currents, and sediment transport) focus on those essential physics that capture the variable wave and current fields. The sediment transport modeling used to describe the movement at Duxbury Beach is founded in the physics of water and sediment movement. These process-based models provide information on the regional sediment transport trends in the presence of time-variable (in direction and height) waves.

Both alongshore and cross-shore models used herein are process-based models, which provide a more robust assessment than models or estimates based solely on empirical equations.

ALONGSHORE SEDIMENT MOVEMENT

Investigation of the alongshore movement of sediment should involve more than just determining the net rate of transport along a stretch of shoreline. The waves and currents driving the movement of sediment result in areas of convergence and divergence that lead to changes in the shape and response of the shoreline. For example, a reduction in the rate of transport along the shoreline results in an area more prone to accretion or reduced erosion. Likewise, an increase in the rate of transport will likely result in an area of increased erosion or reduced accretion. Similar to flow of traffic on an interstate, these changes in the “speed” of the sediment flux result in area of sediment congestion (potential increased deposition) or swifter travel (potential increased erosion).

The goal of the alongshore model is to provide a physically-based representation of alongshore currents and sediment transport driven by breaking waves in the surf zone. To achieve this physically-based representation, it is important to understand what alongshore sediment processes may cause erosion or accretion. Typically, a section of shoreline can be represented as a cell (in the case of Duxbury Beach, every 5 meters was utilized). A certain amount of sediment enters this cell from the updrift side (direction from which the waves advance), and a certain amount leaves the cell to the downdrift side. This sediment balance may vary depending on the wave conditions. There are three possibilities that may be observed for that wave condition:

a. The same amount of sediment enters a cell as leaves the cell.
b. More sediment enters a cell than leaves the cell.
c. More sediment leaves a cell than enters the cell.

The first possibility leads to a stable shoreline. The shoreline neither erodes nor accretes. The second possibility leads to an accumulation of sand in the cell, which is a situation causing accretion (building out of the shoreline) to occur. The final possibility leads to a net loss of sediment in the cell, which causes erosion.

Alongshore sediment transport flux was computed by using the wave transformation results (Chapter 5) to determine nearshore hydrodynamics, and subsequently, the sediment flux (representing the rate of sediment moving) along Duxbury Beach. All wave directional bins were combined to create an average annual sediment transport. When considering an average annual year (waves arriving from various directions), the littoral transport rate is a relatively constant value. While there are some minor reversals of transport rate (i.e., sand moving to the north during certain wave approach conditions), the transport is dominated by north to south movement on a net basis. For example, the High Pines area shows convergence of wave energy during certain conditions, indicating that this is an area of potential reduced erosion. This is shown in the model by a reduced rate of southeast transport. These calculations assume that sediment is available on the beach for transport (e.g., potential transport). If the shoreline is armored (e.g., revetment), or has a reduced sediment supply, the sediment transport rates may vary compared to the values presented herein.

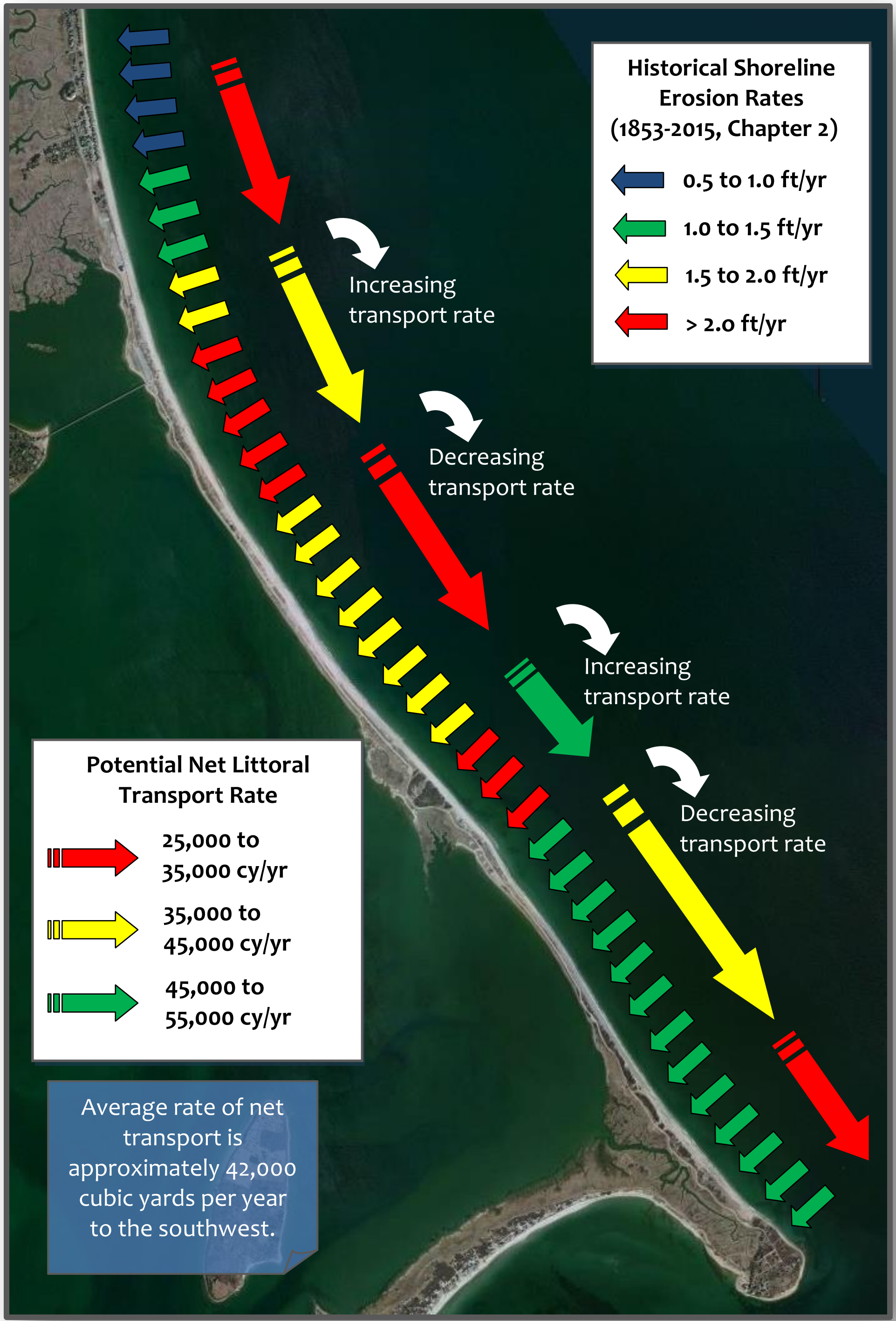
ALONGSHORE SEDIMENT MOVEMENT

As shown in Chapter 2, the Atlantic coast of Duxbury Beach is all eroding, primarily between 1-2 feet per year. The northern portion of the beach has lower shoreline retreat rates due to the existing seawall that inhibits landward migration of the shoreline. Using the shoreline change results from Chapter 2, zones of various erosion rates are delineated along Duxbury Beach. Landward facing arrows indicate shoreline erosion. These variations in erosion rates can be compared to alongshore flux to evaluate the sediment transport processes at work along Duxbury Beach.

Average annual sediment transport rates are moving sand to the southeast, yet there is some variation in the flux magnitude along the shoreline (potential rates vary between approximately 25,000 to 55,000 cubic yards per year). This creates areas of subtle transitions resulting in an acceleration or deceleration ("traffic jams") in the alongshore movement of sediment. In areas where there is a decreasing transport rate, the shoreline should respond with a reduced erosion rate; in areas where there is an increasing transport rate, the shoreline should respond with a higher erosion rate. This means that more (increasing rate) or less (decreasing rate) sediment is leaving the area towards the next cell or grouping of cells alongshore. The historical response in the shoreline is also evident. Areas with increasing transport transition to higher erosion rates (green to yellow to red), while areas with decreasing transport transition to lower erosion rates (red to yellow to green).

Storms result in increased magnitudes of sediment transport. For example, a 50-year return period storm produces alongshore transport rates up to 10 times as large as those for average annual conditions. However, these storms are also relatively short relative to an annual timeframe such that the influence on the alongshore rate is less pronounced. Storms; however, do have a major impact on the cross-shore sediment transport.

Additional details on the alongshore sediment transport model can be found in Appendix 6-A.



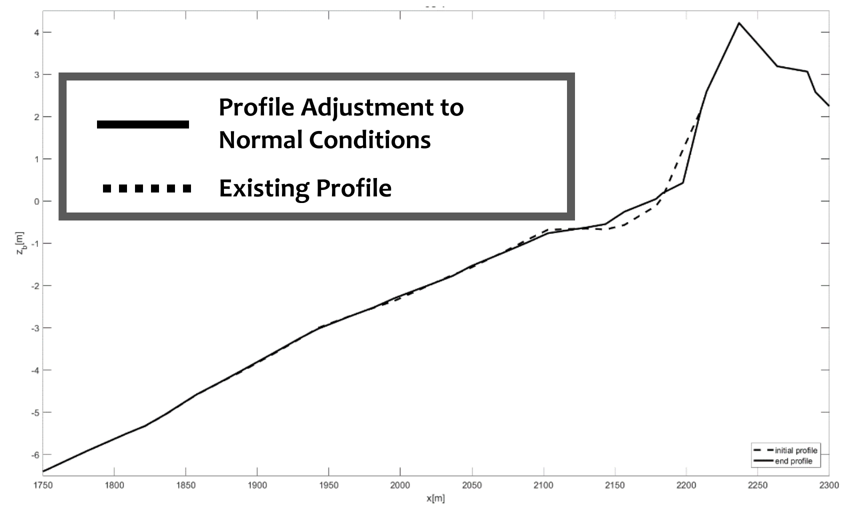
CROSS-SHORE SEDIMENT MOVEMENT

In addition to alongshore sediment transport, physical processes of cross-shore sediment transport were evaluated for key locations along Duxbury Beach. The locations evaluated corresponded to the key resiliency sites identified in Chapter 7. Cross-shore simulations of sand movement were conducted at these sites for normal wave and tide conditions, and more importantly storm conditions (surge and storm waves). Additionally, sea level rise conditions (as presented in Chapter 4) were also considered. In total, three (3) scenarios were evaluated at each of the locations (Chapter 7). These included normal tides with normal waves, a 50-year storm surge with tides and 50-year waves, and a 10-year storm occurring in 2065 with tides and 10-year waves. All these scenarios were evaluated in either hydrodynamic model or wave transformation model.

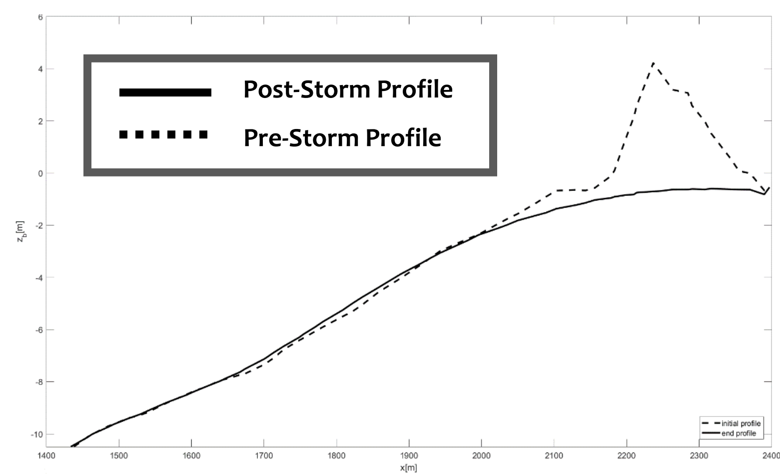
The sediment transport model XBeach (Deltares, 2015), was utilized to simulate sediment transport in cross-shore direction in the nearshore regions of Duxbury Beach. The model was used to evaluate volumetric estimates of cross-shore sediment transport, and to determine the performance of various alternatives at the various site-specific critical locations. As such, the performance of potential nature based solutions could be evaluated.

The XBeach model (Deltares, 2015) includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching. Effects of vegetation and of hard structures have also been included. The model has been validated with a series of analytical, laboratory and field test cases using a standard set of parameter settings.

More details on the cross-shore modeling can be found throughout Chapter 7, presented on graphical cross-sections, and in Appendix 6-B. This includes simulations of existing conditions, as well as cases with the resiliency measures in place.



Response of the beach profile (showing cross-shore movement of sediment) fronting the Pavilion region for normal, average annual tidal and wave conditions. Minor erosion of lower dune face and beach berm.



Response of the beach profile (showing cross-shore movement of sediment) fronting the Pavilion region during a 50-year return period storm event. Model results indicate significant erosion of the dune with a majority of the sediment being pushed landward towards and into Duxbury Bay. The dune has been completely eroded.

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CHAPTER 7

CONCEPTUAL RESILIENCY ADAPTATIONS

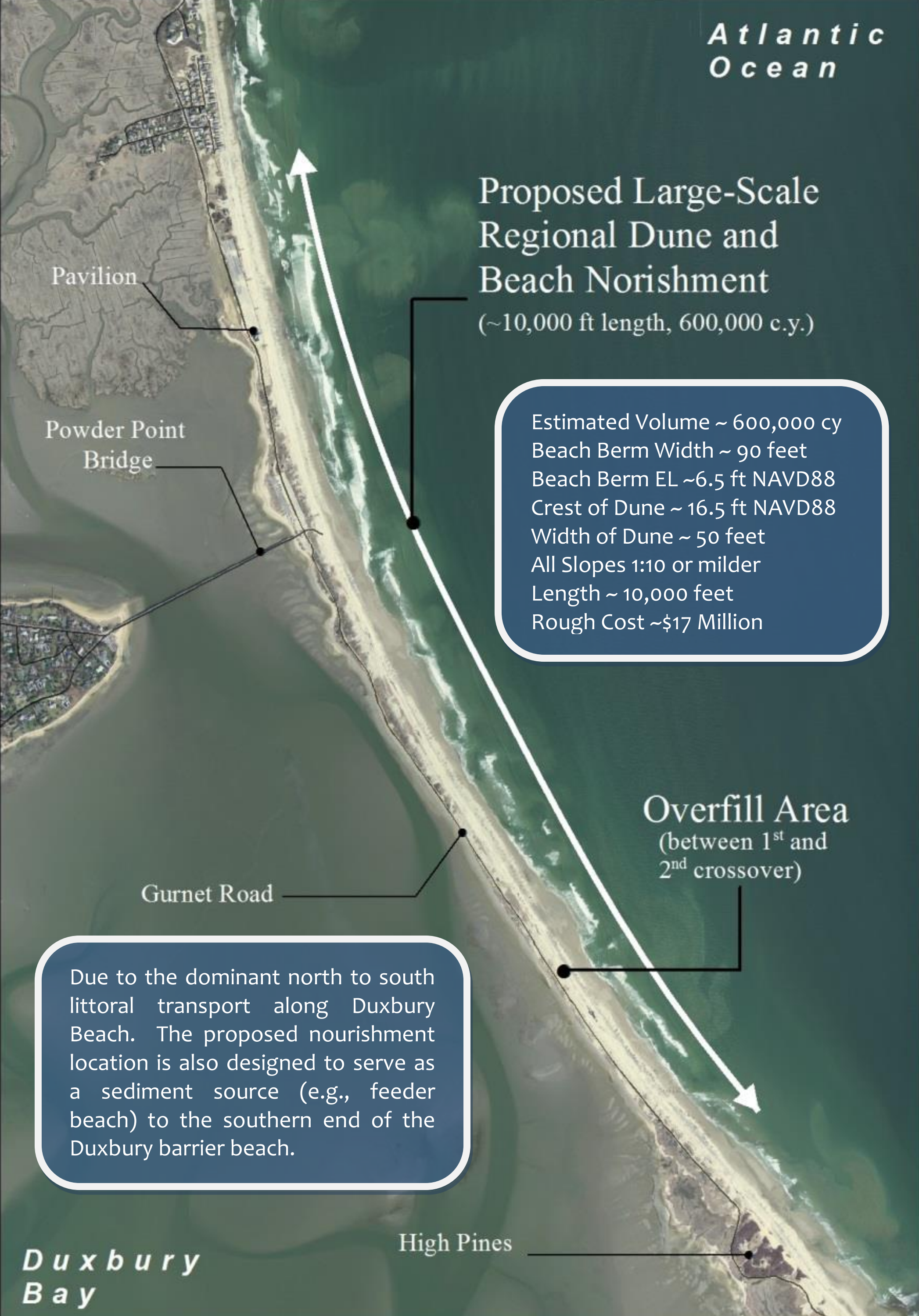
WOODS HOLE GROUP

Duxbury Beach is a dynamic environment with an ever-changing landscape. The barrier beach system is shaped by the wind, waves, currents, and tides that constantly impact the shoreline. While the Duxbury barrier beach has long served as a valuable recreational resource and critical ecological habitat, it also provides crucial storm protection to Duxbury, Kingston, and Plymouth developed mainland shore and the vibrant resources within Duxbury Bay. Duxbury Beach Reservation (DBR) has already conducted numerous efforts to build resiliency for the beach system. In the recent past, these efforts have included, but are not limited to:

- Parking lot improvements and road raising
- Doubling the size of the coastal dune along the landward side of the Pavilion
- Beach and dune restoration efforts following major storms in 1991 and 1992
- Annual beach grass planting (40,000 to 1000,000 culms per year)
- Cobble berm construction on the bay side of the barrier beach
- Drift fence installation
- Multiple relocations of the roadway to work with natural barrier beach processes

Now, the potential acceleration of climate change, sea level rise, and increasing frequency and intensity of erosion inducing events are adding expanded pressure to the durability of the beach system. With these mounting pressures, increased resiliency of the barrier beach is paramount and a more comprehensive and prioritized approach to building resilience is required to supplement the ongoing efforts of DBR. Armed with an improved understanding of the coastal processes that influence and shape the Duxbury Beach landscape, this chapter provides some recommended approaches geared towards improving the overall resilience of the barrier beach system.

Due to the delicate balance of the ecosystem and natural landscape, resiliency options and engineering concepts presented herein are green in nature and designed to preserve the ecological and recreational usages, while balancing the need for improved storm damage protection. Proposed measures are presented in this chapter starting with a larger-scale regional approach. In addition to the regional adaptation measure, site-specific adaptations are also provided for critical locations along the beach. These local resiliency measures are intended to be more near-term attainable and fiscally manageable solutions. For each conceptual adaptation, a priority level, developed with the Duxbury Beach Reservation Technical Committee, and an expected time frame and rough cost (final engineering estimates would be required to develop a detailed cost) are presented. These solutions represent approaches of improving the overall resiliency of the beach system, but in more bite size pieces. Some concepts require additional engineering development and design plans to be completed (e.g., site specific surveys); however, the general concepts are fully developed.



REGIONAL ADAPTATION

One of the primary causes of coastal erosion is a deficit of sediment within the coastal littoral cell. To offset this deficit, nourishing the beach with compatible sediment placement is a logical means for improving the resiliency of a shoreline where such a project is economically feasible. Beach nourishment does not stop erosion, but it does strengthen the system by the addition of compatible material. The damage to landward areas are postponed by extending the shoreline toward the ocean. At a site like Duxbury Beach, the beach also provides a major recreational and ecological benefit. Beach nourishment is typically the most non-intrusive technique for coastal protection and involves placing sand, from an offshore or upland source, in a designed template on an eroding beach. Beach nourishment at Duxbury Beach would be intended to widen the beach, as well as provide added storm protection, increased recreational space, and added habitat area. Although nourished sand is eventually displaced alongshore or transported offshore, the nourished sand that is eroded takes the place of areas that would normally have been lost or eroded during a storm event. Therefore, beach nourishment serves a significant role in storm protection. In addition, beach nourishment is the only alternative that introduces additional sand into the system. For coastlines with a dwindling sediment supply and faced with rising seas, this is critical for long-term success.

The many benefits of beach nourishment, and the ability to control negative environmental impacts with careful design and planning, make beach nourishment a viable resiliency option for Duxbury Beach.

Representative Cross Section

REGIONAL ADAPTATION

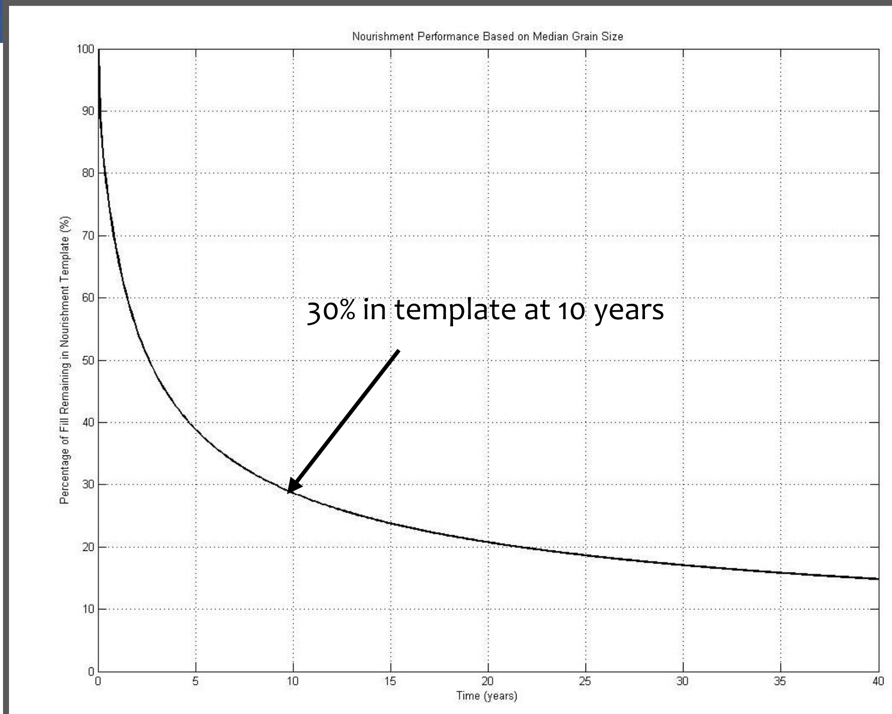
PRIORITY AND TIMING

HIGH PRIORITY

LONG-TERM

A large scale beach nourishment project is the recommended regional adaptation and is considered a high priority. The potential project would be expected to take a long time to plan and permit, primarily due to identification of a sediment source and fund raising.

Since the nourishment material diffuses (spreads) over time, it is possible to evaluate the longevity of the nourishment by looking at the amount of material (by percent) left in the project area. The lifetime of the beach nourishment is based upon the percent of the initial beach fill left within the boundary of the initial fill template. The percentage remaining will decrease with time, but that material is not necessarily lost from the system, it has just spread to regions outside of the original nourishment template. For example, sediment will likely be transported to the southeast. Therefore, although the sediment no longer falls within the initial nourishment template, it has not disappeared from the system as a whole. For the proposed nourishment template, approximately 30% of the material will remain in the original template after 10 years.



A successful beach nourishment project consists of more than simply placing sediment on a beach. Beach nourishment projects are engineered. A beach nourishment template, which consists of numerous design parameters, is based on the characteristics of the site and the needs of a project. Every beach nourishment design is unique, since different beaches in different areas have different physical, geologic, environmental, and economic characteristics, as well as different levels of required protection. The design must consider climatology, the shape of the beach, type of native sand, volume and rates of sediment transport, erosion patterns and causes, waves and water levels, historical data and previous storms, probability of certain beach behaviors at the site, existing structures and infrastructure, and past engineering activities in the area.

The structure of a nourishment template is designed to yield a protective barrier that also provides material to the beach. A higher and wider beach berm is designed to absorb wave energy. Dunes are needed to reduce damage from storms. Nourishment length, berm height and width, dune height, volume, and offshore slope are critical elements of a beach nourishment design. The proposed Duxbury Beach regional adaptation consists of a beach nourishment project spanning approximately 1.9 miles along the northern portion of the barrier beach. This material will spread to the south and serve as a longer term source of material for the southern part of Duxbury Beach. The design also consists of overfill areas (additional sediment) in certain areas (e.g., between the first and second crossover) to bolster the protection at critical shoreline stretches or in areas with increased wave energy (Chapter 5). The proposed project would raise the elevation of the existing dune, increase the beach width by over 100 feet at high tide, and be appropriately sloped for habitat restoration.

A large-scale nourishment project for this area would mitigate the on-going erosion, improve storm damage prevention, provide flood protection for the roadway, improve the recreational resources, and enhance the ecological benefit of the beach.

SITE 1
DUXBURY BEACH PARK PAVILION

The Duxbury Beach Park pavilion, initial constructed in 1941, is the only major structure along Duxbury Beach. The Pavilion has restrooms and showers and offers frozen treats and lunch foods throughout the day. Blakeman's Restaurant also resides in the Pavilion and provides a full service dining option for beach goers. The Pavilion is the primary hub for beach visitors and therefore is an important resource to protect.

Historically, efforts were made to protect the Pavilion and surrounding parking infrastructure through use of various configurations of cement blocks and tie-rods. However, during significant storm events (e.g., the Blizzard of 1978) these methods ultimately failed. More recently, sacrificial dune restoration projects have been conducted to bolster the natural state of the dune and beach system in the vicinity of the Pavilion. As indicated in the Chapter 2, these efforts have had a beneficial impact.

Currently, the existing dune in the vicinity of the Pavilion has narrowed significantly, especially directly in front of the Pavilion. This offers limited protection against storm events. As such, a dune restoration and beach berm enhancement project is recommended at this site. The proposed dune would have a crest elevation of 16.5 feet NAVD88 and increase the total width of the dune to approximately 50-55 feet. A 90 foot wide beach berm is also recommended to provide some wave energy dissipation and protection to the dune as vegetation develops. The total length of the proposed restoration is approximately 1,000 feet long and would require approximately 50,000-60,000 cubic yards of compatible material. Improved beach access pathways (e.g., raised boardwalks over the restored dune) are also recommended to limit potential flood pathways.

The current state of the dunes in front of the Pavilion is less than ideal. The dunes have narrowed to 20-25 feet in width and are sparsely vegetated. The proposed adaptation consists of a dune and beach berm restoration project spanning approximately 1,000 feet of shoreline. The restoration proposes to restore the dune to a similar level as the adjacent healthy dunes while adding a fronting beach berm.

PRIORITY AND TIMING

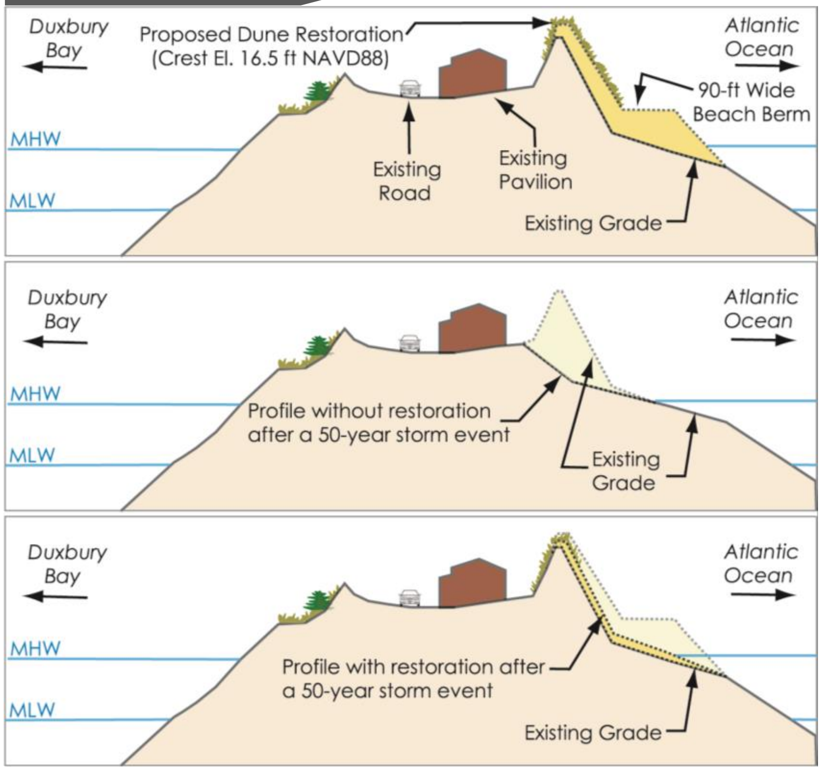
1 *HIGH PRIORITY*

NEAR-TERM

The Duxbury Beach Reservation technical committee ranked this site as the highest priority project. It can be completed in the near-term as no significant studies, engineering efforts, or permitting hurdles are expected. There are already on-going efforts that consider dune enhancement. Engineering design plans and environmental permitting are needed prior to construction of this adaptation measure.

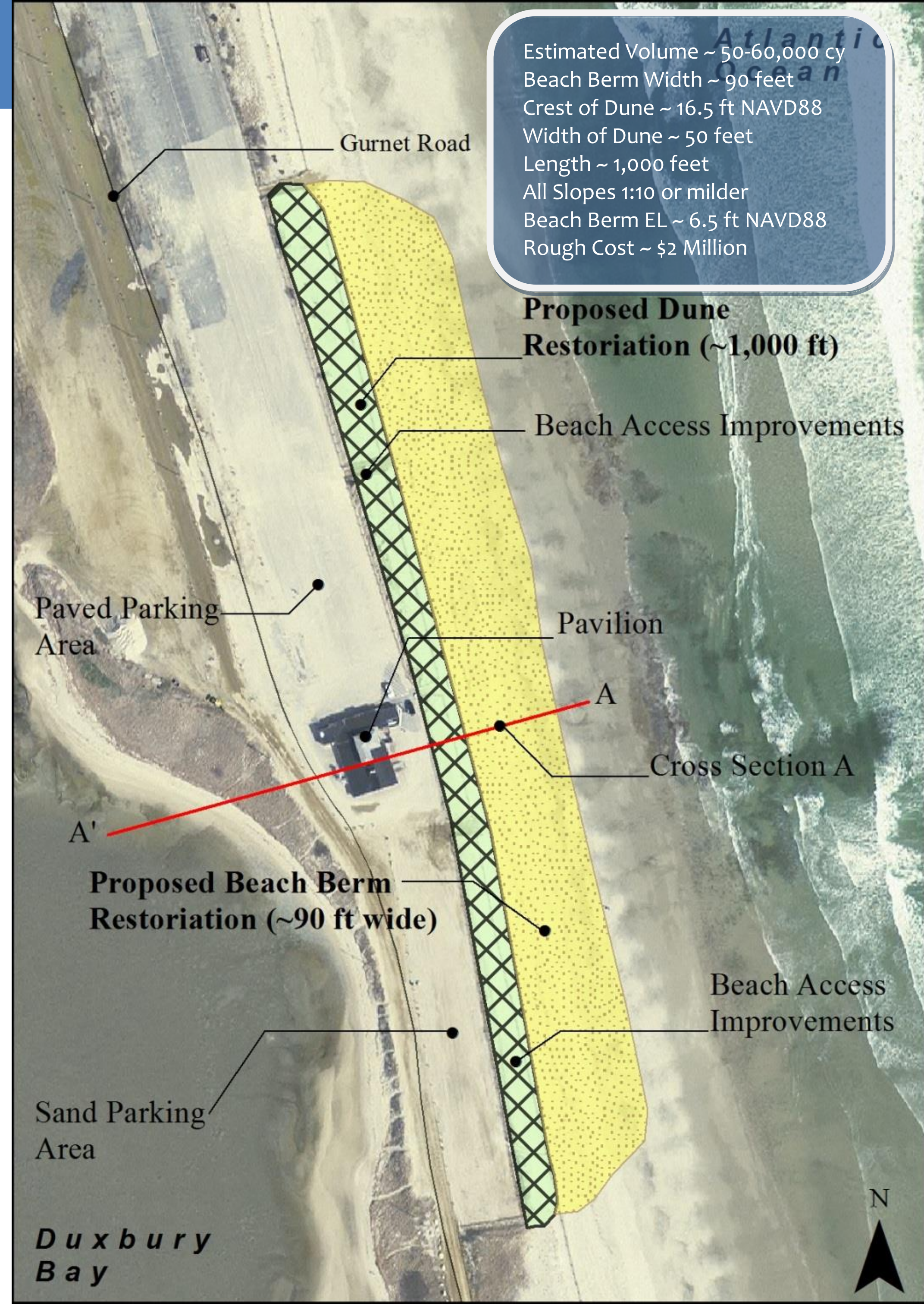
SITE 1
DUXBURY BEACH PARK PAVILION

Cross Section A-A’



The performance of the proposed restoration option is illustrated above. The top panel shows a graphical representation of the proposed dune and beach berm restoration at a cross section in front of the pavilion. The second panel shows the erosion of the existing profile that would be expected to occur if a 50-year storm event impacted the beach. The dashed line shows the pre-storm existing grade, while the solid line shows the post-storm grade. Essentially the dune has been destroyed by the storm. The third panel shows the erosion of the proposed restoration profile caused by the same 50-year storm event. In this case the dune remains.

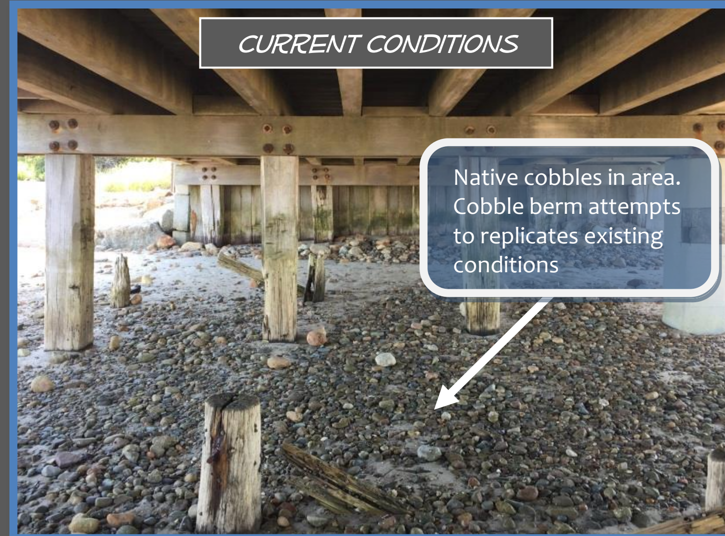
The proposed dune and beach berm restoration provides enhanced protection against moderate to large storm events. While the existing dune may be completely destroyed and the barrier overtopped, the proposed resiliency measure keeps the dune from being overwhelmed and washed away.



SITE 2
POWDER POINT BRIDGE

The original Powder Point Bridge, called the Gurnet Bridge, was constructed in 1892. The bridge shortened an approximate 8 mile trip through Marshfield to under half a mile. In 1987, the bridge was reconstructed replicating the original wooden design. Currently, the bridge stands as the longest wooden bridge in America.

On the eastern side of the bridge, where it connects to the barrier beach, the shoreline adjacent to the abutments is experiencing ongoing erosion due to tidal currents and wind-generated waves produced in Duxbury Bay. Attempts to mitigate this erosion appear to have consisted of loosely placed large armor units next to the bridge abutments; however erosion on either side of the abutments and scour under the bridge seem to have persisted. The proposed resiliency measure at this location consists of creation of a cobble berm along the eroded shoreline area, with larger armor units against the wooden bulkhead and rubber fenders around the piles to avoid impact damage from the cobbles.



PRIORITY AND TIMING

1 HIGH PRIORITY

NEAR-TERM

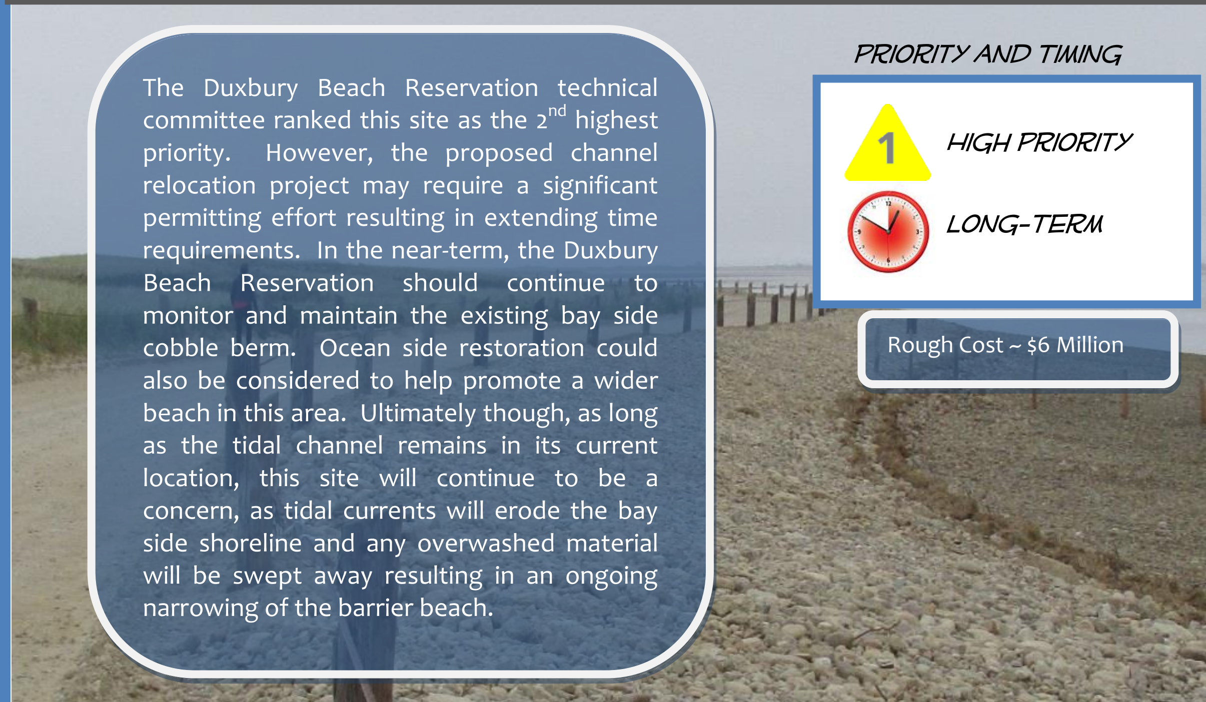
The Duxbury Beach Reservation technical committee ranked this site as the 3rd highest priority project. It can be completed in the near-term as no significant studies, engineering efforts, or permitting hurdles are expected. Engineering design plans and environmental permitting would need to be conducted prior to construction of this adaptation measure.

SITE 3
BAY SIDE CHANNEL

One of the primary tidal channels within Duxbury Bay (running under the Powder Point Bridge) flows directly adjacent to the bay side shoreline of the barrier beach. Over approximately a 750 foot long stretch, the tidal channel runs extremely close to the shoreline and creates higher velocities that are prone to eroding the barrier beach. As shown in the hydrodynamic model (Chapter 4), this has produced some significant erosional pressure on the back side of the barrier beach in this region, which would be even further heightened during storm events. In addition, not only do the tidal currents induce erosion, but any overwash sediment arriving from the ocean side of the barrier either fills in the channel and must be removed anthropogenically, or is swept away by the tidal currents limiting the barrier width further. This interrupts the natural barrier beach overwash process that results in the rolling landward of the barrier beach and maintains some ongoing maintenance of beach width. Without this process, the barrier beach in this location will continue to narrow and result in a vulnerable area for breaching under future storm conditions and climate change.

However, it isn't just the barrier beach that stands to benefit from channel relocation in this region. The channel itself also may be less prone to shoaling conditions. For example, during a large storm and overwash event, excess sediment could hinder navigation, at least temporarily. This infilling could require maintenance actions or, at minimum, a temporary closure until the tidal currents remove the sediment.

Additionally, potential excess dredge material from the channel relocation could be beneficially re-used to support salt marsh restoration projects at the High Pines region (Site 6). Therefore, potential channel relocation could address multiple resiliency measures.



The Duxbury Beach Reservation technical committee ranked this site as the 2nd highest priority. However, the proposed channel relocation project may require a significant permitting effort resulting in extending time requirements. In the near-term, the Duxbury Beach Reservation should continue to monitor and maintain the existing bay side cobble berm. Ocean side restoration could also be considered to help promote a wider beach in this area. Ultimately though, as long as the tidal channel remains in its current location, this site will continue to be a concern, as tidal currents will erode the bay side shoreline and any overwashed material will be swept away resulting in an ongoing narrowing of the barrier beach.

PRIORITY AND TIMING

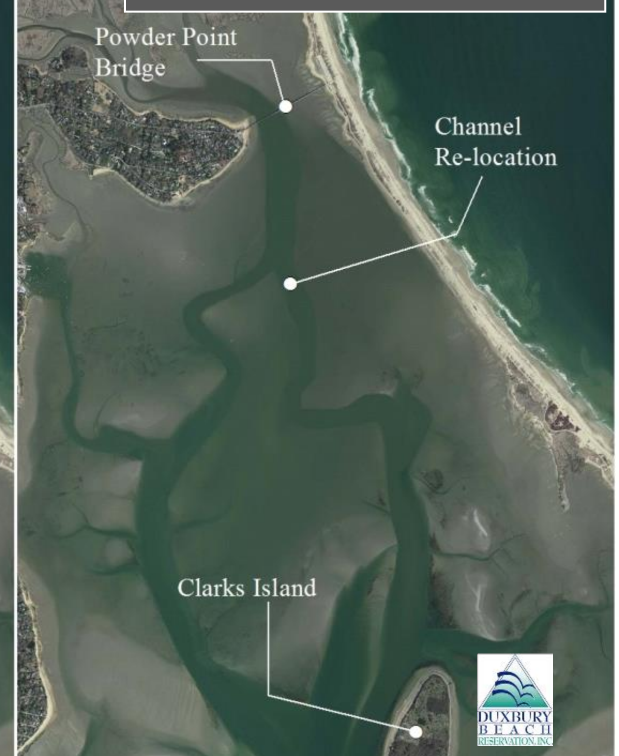
1 *HIGH PRIORITY*

LONG-TERM

Rough Cost ~ $6 Million

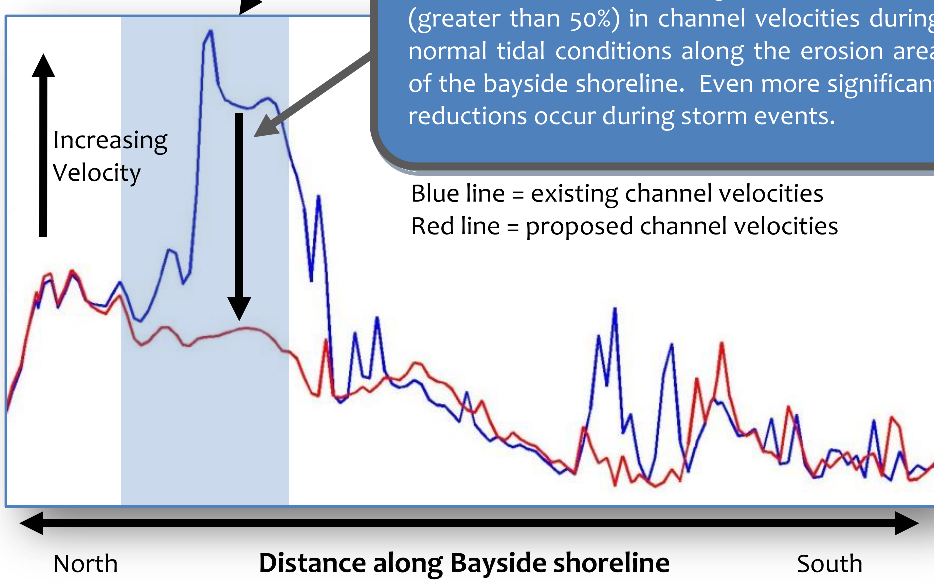
CURRENT CHANNEL

PROPOSED CHANNEL



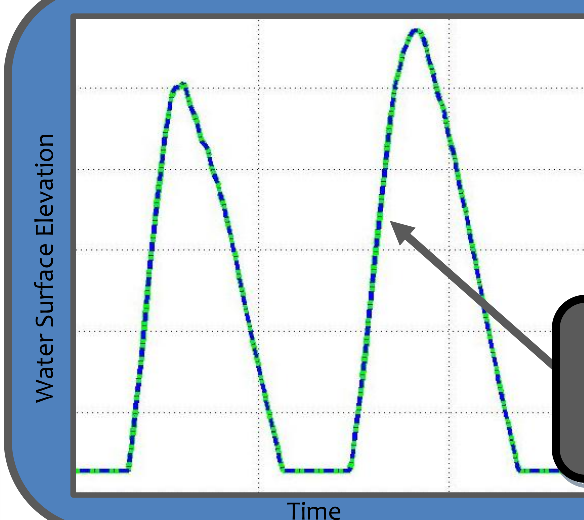
SITE 3
BAY SIDE CHANNEL

The conceptual channel design simulated in the model resulted in a significant reduction (greater than 50%) in channel velocities during normal tidal conditions along the erosion area of the bayside shoreline. Even more significant reductions occur during storm events.



The proposed channel location was developed based on hydrodynamics in the system and avoidance known shellfish and oyster farm lease areas. The exact channel layout could be further refined in an engineering design phase such that it carefully avoids resources (shellfish, oyster beds, etc.). Once a preferred orientation is determined, bathymetric surveys would be conducted to determine the volumes of potential dredging required. The hydrodynamic modeling tool develop under this project (Chapter 4) could then be implemented to assess the overall stability of the channel (e.g., would the rate of shoaling of the channel be increased, decreased, or remain the same), appropriate channel dimensions, and the changes to the hydrodynamics and sediment transport.

With known dredge quantities, the amount of material transferred from the new proposed channel to fill in the old channel, as well as the amount of excess material for potential marsh restoration projects (e.g. Site 6), could be determined.



The hydrodynamic modeling showed no change in the tidal exchange or flushing of the marsh system north of Powder Point Bridge with the proposed channel relocation.

Water surface elevations in upper marsh.
Green = Existing Channel
Blue = Proposed Channel

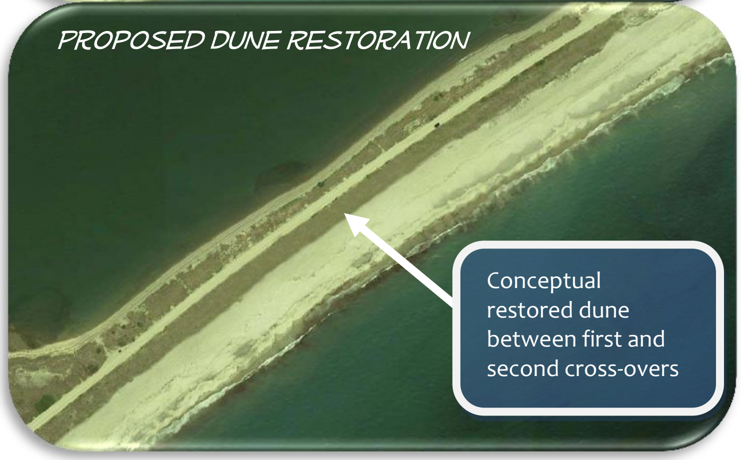
SITE 4
1ST AND 2ND CROSSOVER

The area between the first and second crossovers along Duxbury Beach is one of the narrowest sections of the barrier beach system. This also is a region that experiences increased wave energy during normal conditions and storm events (Chapter 5).

In the regional beach nourishment, this is an area where an overfill is recommended. However, prior to a large-scale nourishment project, a dune restoration project in this area would provide increased resiliency to the barrier beach and dune system, as well as protect the roadway.

Wave modeling indicated this as a location of focused wave energy, suggesting a higher erosion potential. In stretches between the crossovers, the dune has narrowed to less than 35 feet in width and is at elevations similar or just above the roadway.

The proposed dune restoration aims at increasing the resiliency of the area between the first and second crossover, while waiting for the longer-term solution of the large-scale regional beach nourishment project. The proposed restoration consists of a restored dune spanning approximately 1,700 feet in length with a crest elevation of 16.5 feet NAVD88. The dune crest is proposed to be approximately 65 feet wide. This resiliency adaptation, along with Site 1, offer a unique opportunity to evaluate the performance of a dune only restoration project (Site 4) against a dune and beach berm restoration project (Site 1).



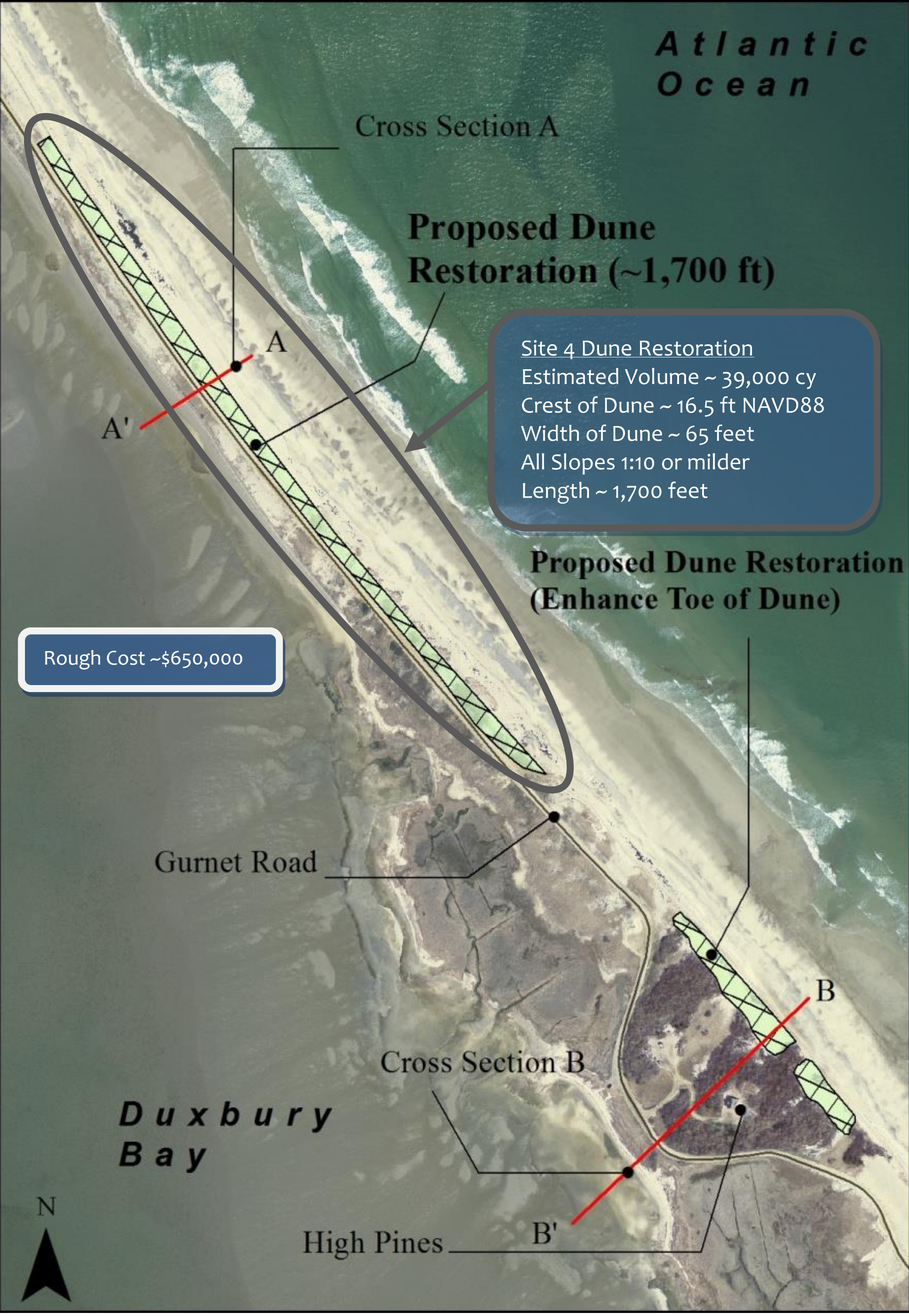
The Duxbury Beach Reservation technical committee ranked this site as the 4th priority site, indicating a medium priority. It can be completed in the near-term as no significant studies, engineering efforts, or permitting hurdles are expected. Engineering design plans and environmental permitting would need to be conducted prior to construction of this adaptation measure.

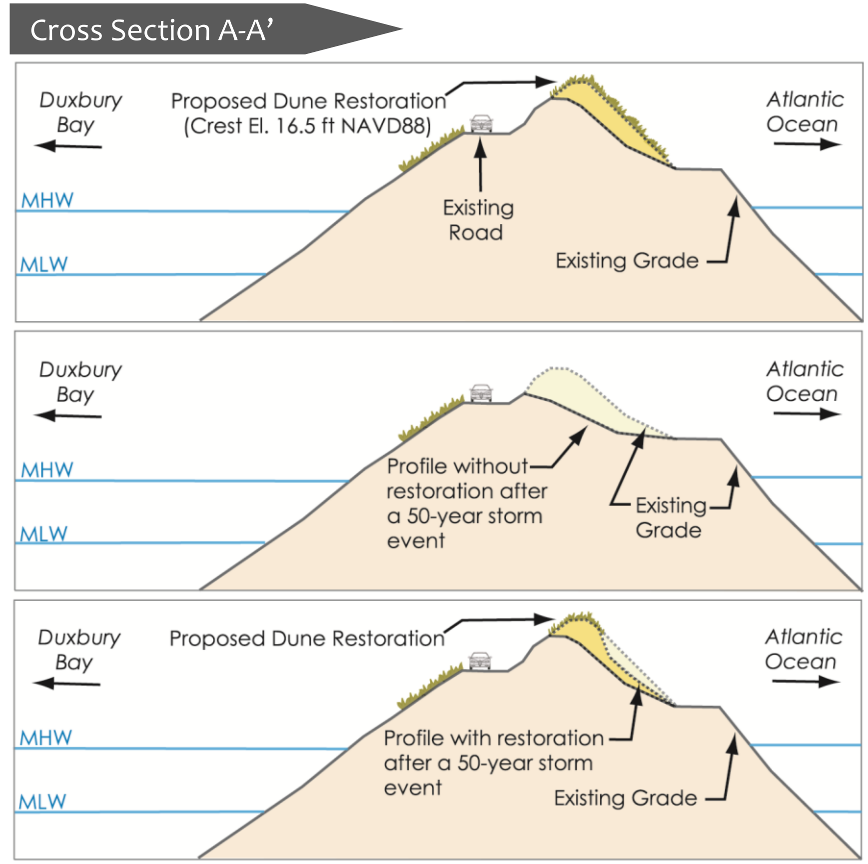
PRIORITY AND TIMING

2 *MEDIUM PRIORITY*

NEAR-TERM

SITE 4
1ST AND 2ND CROSSOVER





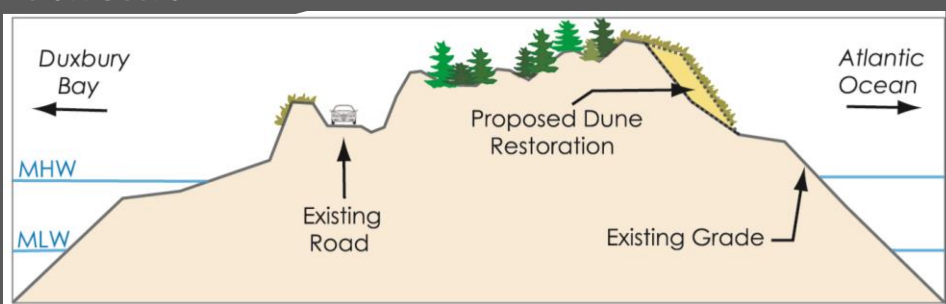
The performance of the proposed resiliency project at Site 4 is illustrated above. The top panel shows a graphical representation of the proposed dune restoration at cross section A-A'. The second panel shows the erosion of the existing profile that would be expected to occur if a 50-year storm event impacted the beach. The dashed line shows the pre-storm existing grade, while the solid line shows the post-storm grade. Essentially the dune has been destroyed and the beach would be overwashed. The third panel shows the erosion of the proposed dune restoration profile caused by the same 50-year storm event. Again, the dashed line shows the pre-storm restored grade, while the solid line shows the post-storm grade. In this case the dune provides increased protection to the roadway and back barrier beach.

SITE 5
HIGH PINES

High Pines, a drumlin located approximately a mile south of the Powder Point Bridge, represents a critical anchor point for the Duxbury barrier beach. While High Pines consists of large sand dunes on the surface, below the surface lies glacial till that makes this area more resilient than the connecting ribbons of sand to the north and south. However, it is still important to actively maintain the High Pines area since this is a critical connector for the entire barrier beach system.

Currently, the High Pines area experiences ongoing erosion at the base of the wind-blown sand dunes facing the Atlantic Ocean. These dune scarps have been maintained through time by DBR, and as part of the proposed resiliency approach should be continually maintained and enhanced to ensure stability of the High Pines anchor point.

Cross Section B-B'

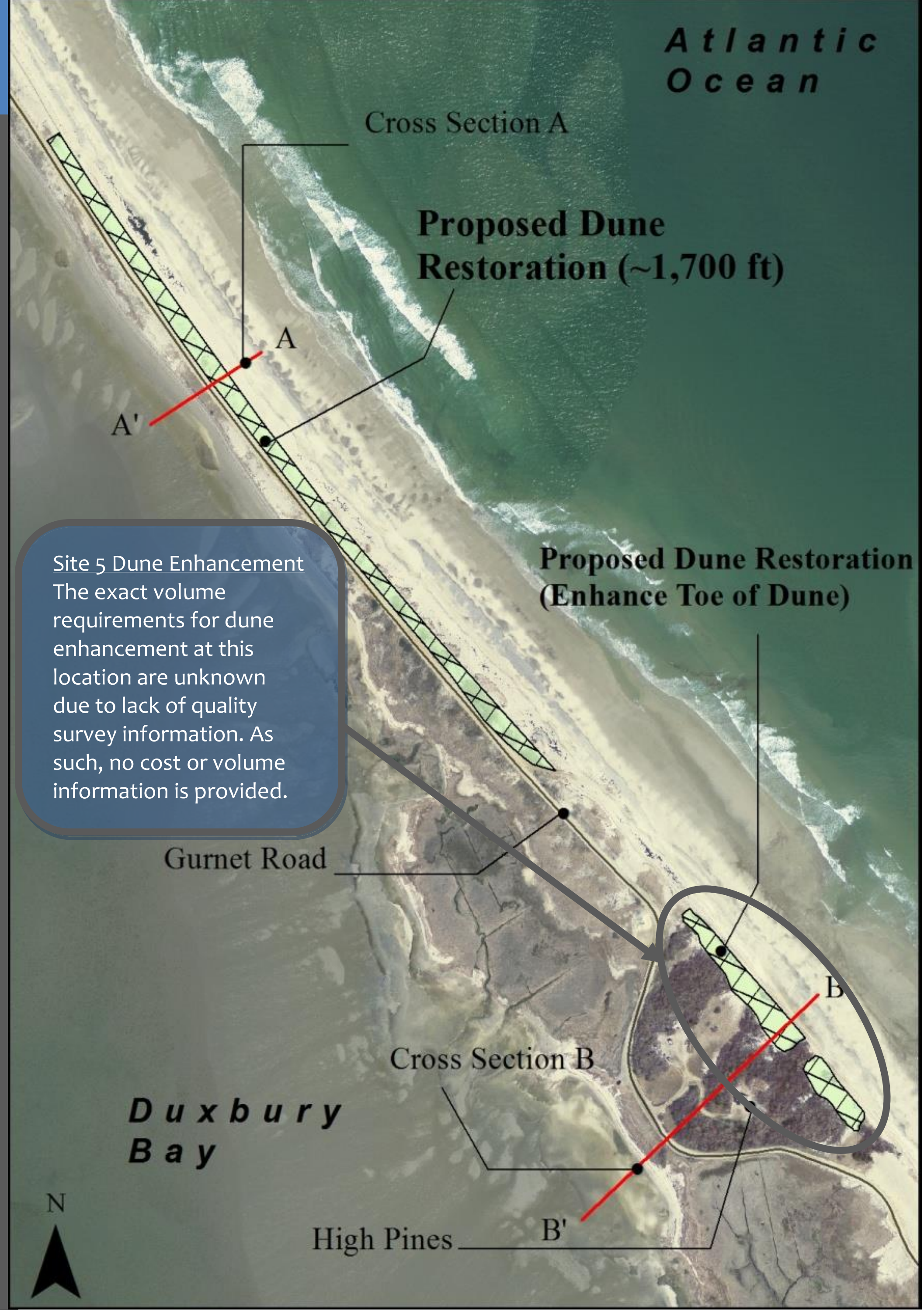


PRIORITY AND TIMING

LOWER PRIORITY

MID-TERM

The Duxbury Beach Reservation technical committee ranked this site as a lower priority site, due to the overall resiliency of the underlying glacial till and less critical nature of the erosion (wider dune and beach).



Site 5 Dune Enhancement

The exact volume requirements for dune enhancement at this location are unknown due to lack of quality survey information. As such, no cost or volume information is provided.

SITE 6
HIGH PINES SALT MARSH

View of existing salt marsh from the southeast. A majority of this area historically was a healthy salt marsh, while now it is primarily tidal flats. All that remains is some smaller isolated islands of marsh.

View of existing salt marsh from the east. Some spines of the former salt marsh still exist with tidal creeks running in between the spines. This area is proposed to be restored to its historic state.

View of existing salt marsh from the north. The overall loss of salt marsh area compared to historic conditions is dramatic. The resiliency project for this location is geared towards returning the marsh to its former levels.

On the bayside, salt marsh resources currently exist to the southeast and northwest of the High Pines drumlin. This is a valuable ecological resource, which also provides protection to the thin barrier beach section just southeast of High Pines. The salt marsh likely originally developed at this location due to the more stable nature of High Pines region.

The goal of the proposed resiliency project at this site is to restore the salt marsh system to a state similar to historical conditions, thereby enhancing ecological resources and also improving resilience of the back side of the barrier beach. This would especially be beneficial to the barrier beach south of High Pines, where the beach width is particularly narrow in the vicinity of the 3^{rd} crossover.

The map from 1916 above shows the historic location and extent of the salt marsh (green outline) that existed adjacent to the High Pines region on the bayside of the barrier beach. The yellow dotted line shows the location and extent of the salt marsh as it existed in 2013. This demonstrates the significant loss of salt marsh over the last century, primarily due to erosion and sea level rise. The proposed resiliency project for this site is aimed at re-creating the salt marsh as it historically existed by expanding the area, specifically to the southern portion of the region.

PRIORITY AND TIMING

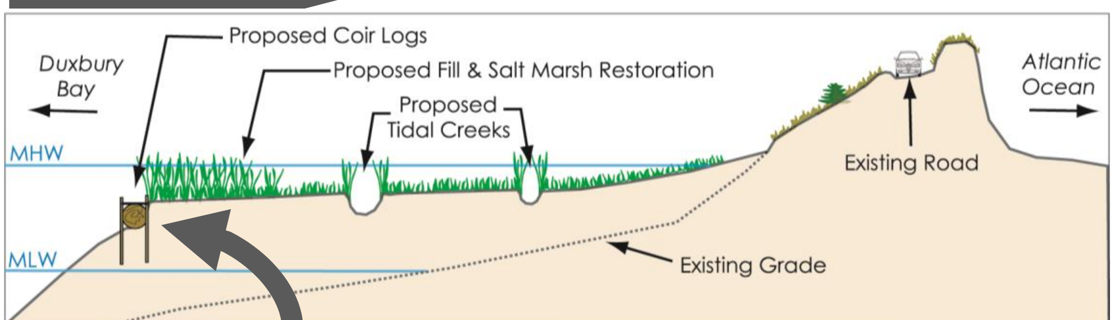
3 *LOWER PRIORITY*

LONG-TERM

The Duxbury Beach Reservation technical committee ranked this site as a lower priority project. It is expected to be a long-term project that would require significant planning, permitting, and additional engineering efforts. An appropriate source of sediment would also be required to raise the proposed marsh to an adequate grade to promote salt marsh growth. One potential source to consider would be utilizing compatible dredge material from the Site 3 resiliency project.

SITE 6
HIGH PINES SALT MARSH

Cross Section A-A'



The proposed wetlands restoration project at this site consists of raising the existing grade to adequate elevations to support marsh growth, creating and improving the tidal creek network to deliver sediment and salt laden water to the restored marsh, and installing a biodegradable coir log edge (or similar) to help stabilize the sediment placement prior to vegetation growth. Once the grades and creeks are created, the restored marsh areas would be planted with appropriate vegetation. The exact design and volume requirements would need to be refined based on more site-specific survey information.

WOODS HOLE GROUP

DUXBURY BEACH RESERVATION, INC.

SITE 7
3RD CROSSOVER

There are three maintained crossovers along Duxbury barrier beach that allow beach goers and vehicles access from the roadway to the beach. These crossovers run across the dune and can be closed seasonally for various reasons (e.g., bird nesting). The third crossover, located south of High Pines, is situated on the narrowest section of the barrier beach and has been more difficult to maintain due to storm impacts and overwash effects. The third crossover is also located in an area of higher wave energy (Chapter 5) and therefore is prone to more management concerns. As such, the Duxbury Beach Reservation Technical Committee flagged the third crossover as a problem area and has already planned on moving this feature.

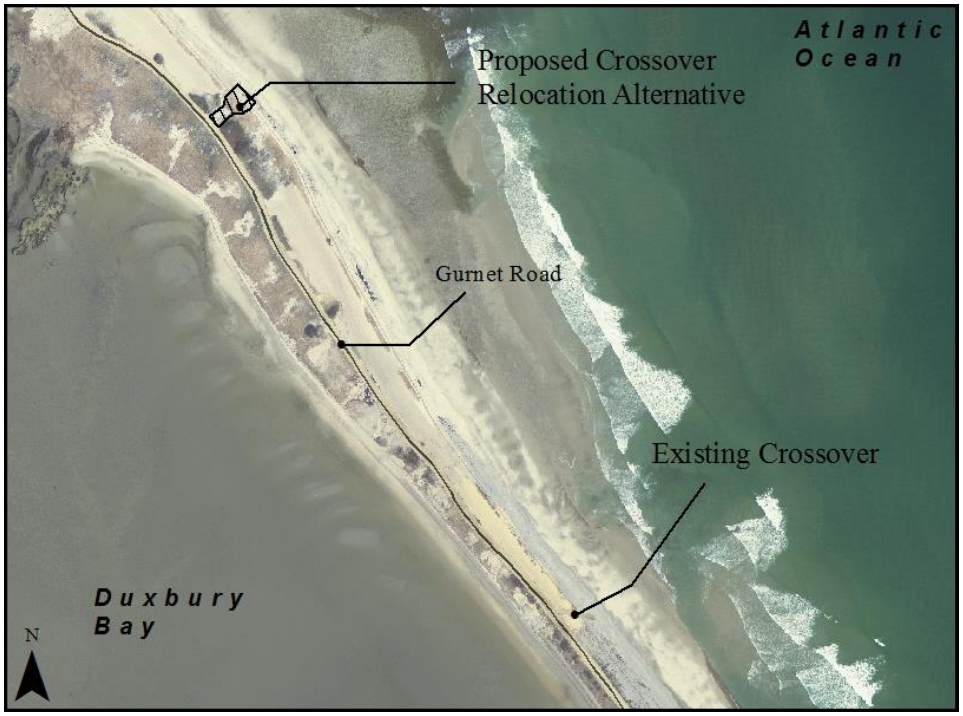
The current location of the third crossover is not ideal given the ongoing coastal processes and existing beach width. The easiest, and least intrusive, solution is to move the third crossover to a more stable and easily maintained location. One potential location, based on the apparent stability of the beach (dune vegetation), historic shoreline change (Chapter 2), and wave energy (Chapter 5) is presented in the adjacent panel. The exact orientation of the crossover would require some site specific surveying and analysis work, but should align with the policies set-up for the other crossover locations. Additionally, the existing crossover location should be completely restored and repaired to match native conditions of the beach and dune system.

PRIORITY AND TIMING

2 *MEDIUM PRIORITY*

NEAR-TERM

The Duxbury Beach Reservation technical committee ranked this site as a medium priority project and has already begun the planning for moving this crossover. The timing of moving the 3rd crossover would be expected to be fairly swift. The project is not expected to have significant engineering or permitting requirements.

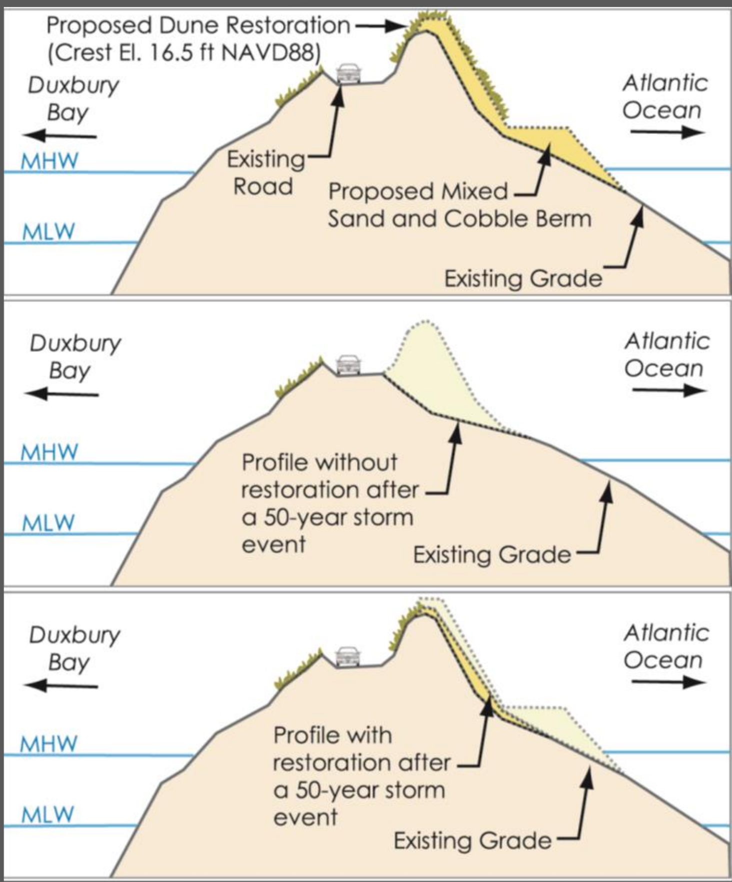


SITE 8
BAY SIDE NEW ROAD

South of the third crossover, where the overall beach width remains narrow, the Duxbury Beach Reservation has recently relocated the road and bolstered the barrier with cobble nourishment on the landward side of overwashes. However, due to the lack of overall beach width in this region, the barrier beach and roadway remain vulnerable to coastal erosion, wave overtopping, and overwash. Various forms of sand fencing have been installed throughout this region to attempt to bolster the beach system through capturing wind-blown sediment; however, this alone cannot provide adequate resiliency for this region. The area also consists of larger median grain size material (Chapter 3) than areas further to the north along Duxbury Beach. There is a mix of cobbles and sand that comprise much of the beach berm and dune system. As such, the proposed resiliency measures attempt to more closely mimic the native grain size distribution in the area by recommending a sand and cobble berm in this region to provide added resiliency to the roadway and reduce breach potential.

SITE 8
BAY SIDE NEW ROAD

Cross Section A-A’



The performance of the proposed resiliency project at Site 8 is illustrated above. The top panel shows a graphical representation of the proposed dune and sand/cobble berm restoration at cross section A-A’. The second panel shows the erosion of the existing profile that would be expected to occur if a 50-year storm event impacted the beach. The dashed line shows the pre-storm existing grade, while the solid line shows the post-storm grade. Essentially, the existing beach is unable to protect the road and would be overwashed. The third panel shows the erosion of the proposed dune and beach restoration profile caused by the same 50-year storm event. The dashed line shows the pre-storm restoration grade, while the solid line shows the post-storm grade. In this case the dune and beach berm provide increased protection to the roadway and back barrier beach.

The primary proposed resiliency project at Site 8 consists of a dune restoration coupled with a mixed sand and cobble berm. Due to the narrow width of the beach in this area, the beach berm is designed to be 75-100 feet wide to provide added protection to this region. A secondary management option that should be considered at this location is ongoing monitoring of the roadway itself. Management actions would continue to raise and resurface the roadway as necessary. This management approach could be carried out while waiting for the mixed cobble and sand based nourishment approach presented here.

This proposed project, along with the resiliency projects proposed at Site 1 and 4, offer a unique opportunity to evaluate the performance of potential resiliency approaches and designs through comparisons of dune only restorations, dune and beach restorations, and mixed grain size restoration projects.

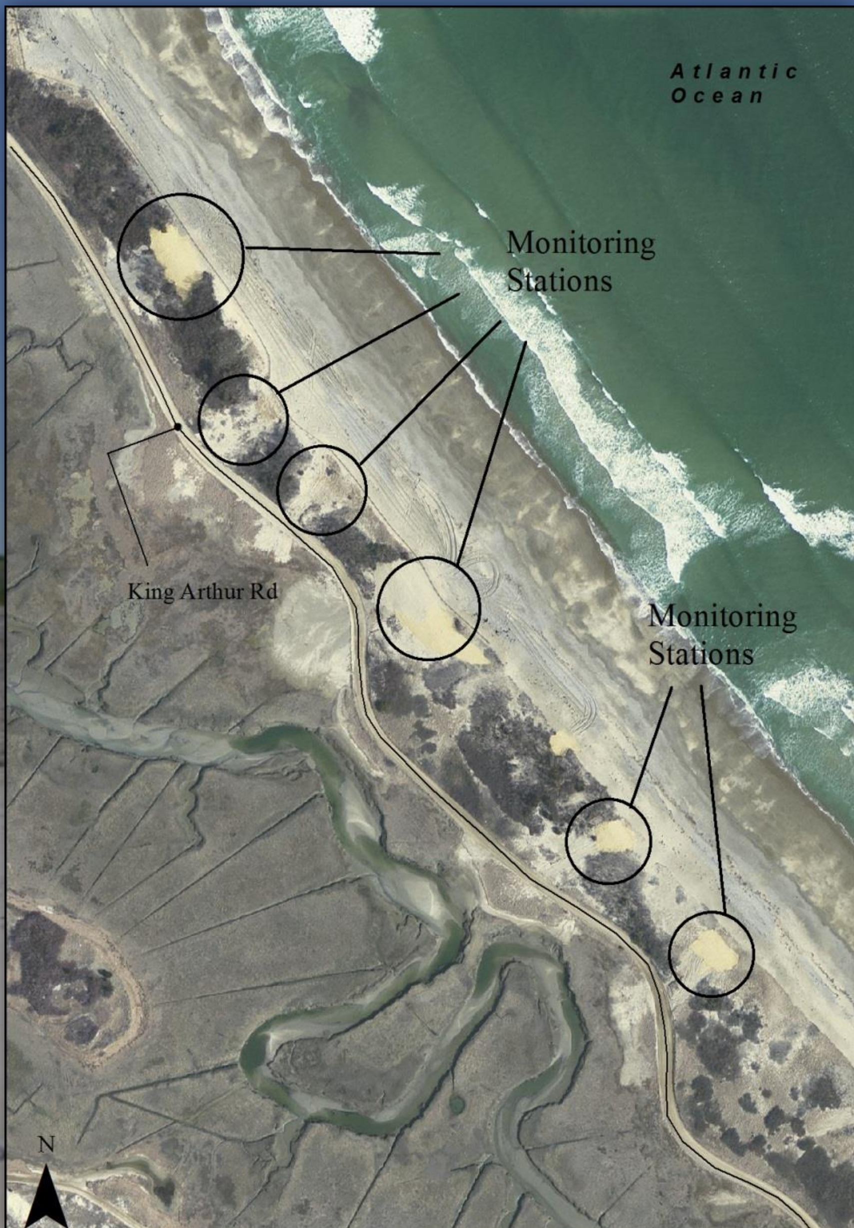
PRIORITY AND TIMING

2 *MEDIUM PRIORITY*

MID-TERM

The Duxbury Beach Reservation technical committee ranked this site as a medium priority project. Engineering design plans and environmental permitting would need to be conducted prior to construction of this adaptation measure. In terms of timing, this would be considered a mid-term project. In the meantime, ongoing monitoring and road maintenance should continue to be conducted.

SITE 9
PLUM HILLS



The Plum Hills area is located on the southern portion of Duxbury Beach (just before reaching Gurnet Point). The area consists of higher vegetated dunes and "hills" in between lower elevation areas that have breached and overwashed in the past. Efforts have been made to restore these breached areas and protect the roadway to Gurnet Point, likely following storm events that have pushed sediment onto the roadway.

At this site, ongoing monitoring is recommended, not only to evaluate the long-term viability of the roadway, but also to ensure that potential breaches and breakthroughs do not have a detrimental effect on the backing salt marsh system.

The Duxbury Beach Reservation technical committee ranked this site as a lower priority project. Currently, it is recommended that the area continues to be monitored and dunes repaired, especially in overwash prone locations. Restoration of these areas has been conducted in the past and can continue to be monitored and restored as necessary. Potential modifications to restoration designs should be considered using an adaptive management framework to determine if there are more effective ways to restore breached locations in the future.

PRIORITY AND TIMING

3 *LOWER PRIORITY*

MID-TERM

WOODS HOLE GROUP

DUXBURY BEACH RESERVATION, INC